MONTHLY WEATHER REVIEW

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MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription: Domestic, $3.00; Foreign, $4.00; 30¢ per copy. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

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(Continued on inside back cover)

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

The printing of this publication has been approved by the Director of the Bureau of the Budget, February 11, 1952

DEPARTMENT OF COMMERCE
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A POSSIBLE QUANTITATIVE USE OF MEAN CIRCULATION CONCEPTS IN DAILY FORECASTING

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ABSTRACT

The question of the operation of large-scale controls in day-to-day weather map evolutions is discussed. To explore the usefulness of these concepts in daily forecasting, the problem of forecasting the passage of summertime cold fronts at Kansas City is used. More-or-less standard techniques are used to develop an objective method of forecasting these frontal passages, and its deficiencies are discussed. A technique employing certain aspects of the 5-day mean 700-mb. chart as a means of eliminating these deficiencies is investigated. Results suggest that it is possible to use certain features of a prognostic 5-day mean 700-mb. chart to improve on the results of an objective forecasting method.

INTRODUCTION

The question of long-term and large-scale weather controls has long been examined. Baur [1] discusses long-range weather controls (*Grosswetter*) and sets forth nine "empirical theorems" substantiating the reality of the concept. Further, he defines the term *Grosswetterlage* as "the mean pressure distribution (at sea-level) for a time interval during which the position of the stationary (steering) cyclones and anticyclones and the steering within a special circulation region remain essentially unchanged." He adds that restriction to mean surface pressure distribution is necessary in order to be able to apply the definition to the years before aerological observations were available, but that the existence of such Grosswetterlage imply constancy of pressure distribution in the middle troposphere.

Namias [2] reasons at some length on the reality of these large scale controls and says:

> Yet the interrelationship [between tracks of cyclones and anticyclones, and centers of action] does not *prove* that the behavior of the individual systems of the daily maps is determined by the centers of action . . . . At present there seems to be no satisfactory method of proving the causal and governing nature of the centers of action as opposed to the view that they are only statistical reflections . . . . It seems to the author [Namias] that the moderate success obtained in predicting 30-day average circulation patterns from preceding sequences of such patterns is an indication of ***physical reality of the means***. [These last italics supplied.]

If there is an element of reality in these concepts of Grosswetterlage, they should rightfully be a necessary adjunct in the entire field of daily forecasting. With these views in mind, a possible objection to a number of objective forecasting methods which have been devised lies in the fact that they are developed from a group of data taken from a variety of Grosswetter regimes. This would seem to be disadvantageous on two points:

1. Unless one deliberately sets out to include a full range of Grosswetter types in the developmental *and* the test data, a test is likely to indicate a breakdown of the objective method, not necessarily because of the lack of effectiveness of the variables used, but simply because the developmental and test data comprise predominantly different Grosswetter types. This is particularly true when the developmental sample comprises one time series of data, and the test sample another.
2. If a variety of Grosswetter types are included in the developmental data, discrete grouping of the elements to be forecast becomes difficult to achieve because the predictor variables tend to exert influences which vary from one type to another.

The purpose of this paper is to explore the applicability of these concepts of large-scale controls to the daily forecast problem. An assumption that is suggested may be stated as follows: There exist large-scale features of the circulation which exercise some control over certain features of the daily maps, and further, these large-scale features are at least partly portrayable by maps of time averages of pressure, or height of a pressure surface.

SELECTION OF SPECIFIC FORECAST PROBLEM

To investigate the utility of these concepts in the daily forecast, the problem of predicting cold or occluded front passages at Kansas City was chosen. While the choice was somewhat arbitrary, still there are certain aspects of the problem which make it a reasonable choice. By dealing with fronts already in existence, the question of their subsequent movement becomes more closely allied with the flow itself rather than a thermodynamic problem such as would be the case if precipitation or cloudiness had been chosen.

DEVELOPMENT OF FORECASTING METHOD

DATA SELECTION AND INITIAL STRATIFICATION

Cases of the 1230 GMT surface chart in which a cold, stationary, or occluded front occurred within the area indicated in figure 1 were chosen as the basic data. The specific problem was whether or not these fronts would pass Kansas City within the subsequent 24-hour period. The summer months—June, July, and August—were con-

FIGURE 1.—Schematic illustration of basic data tabulation. Cases of the 1230 GMT surface map selected when a cold, occluded, or stationary front appeared within outlined area. Elements tabulated were (1) shortest distance between front and Kansas City (in nautical miles); (2) isallobaric gradient across front, i. e., 3-hour tendency at A minus 3-hour tendency at B (interpolated if necessary); and (3) whether or not front passed Kansas City within the following 24 hours.

TABLE 1.—*Percentage of total frontal cases in which front passed Kansas City within subsequent 24 hours, by groups from figure 2*

	Dependent period June, July, August 1947–50	Test period June, July, August 1951–53 (except July 1951)
Group 1	2	2
Group 2	18	8
Group 3	30	24
Group 4	64	55
Group 5	89	79

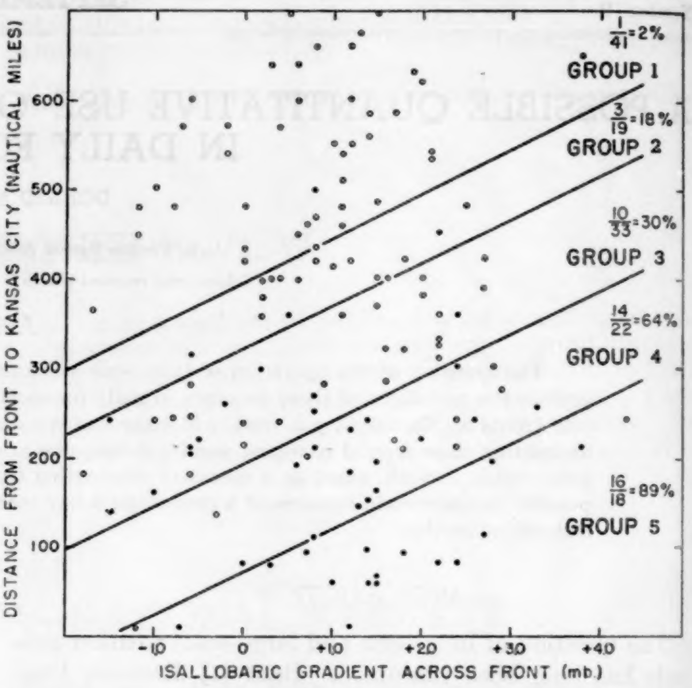

FIGURE 2.—Scatter diagram relating distance from Kansas City to the front and the isallobaric gradient across the front (both measured from 1230 GMT surface chart) to the subsequent passage (●) or non-passage of that front at Kansas City. Ratios are number of cases of passage (numerator) to total number of cases in group. Data from June, July, August 1947–1950 inclusive.

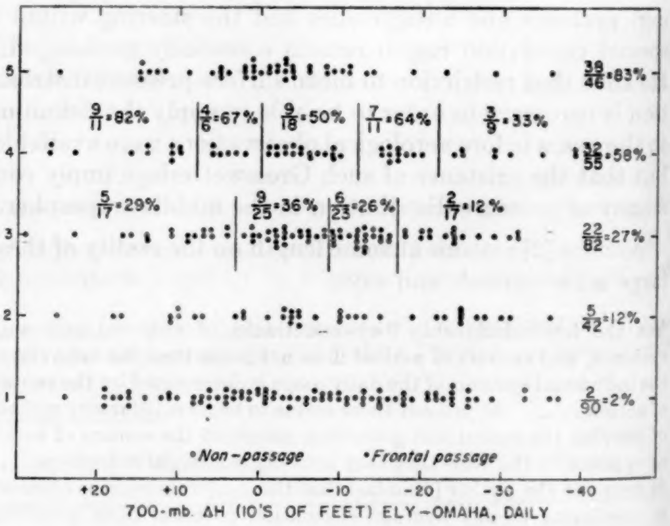

FIGURE 3.—Scatter diagram relating initial stratification as determined from 1230 GMT surface data (fig. 2) and the difference in 700-mb. height from Ely, Nev., to Omaha, Nebr. (Ely minus Omaha), taken from 0300 GMT 700-mb. chart of same date as surface chart, to the subsequent passage or non-passage of the front at Kansas City. Ratios are number of passages (numerator) to total number of cases in group or subsection. Data from June, July, August 1947–1953 inclusive, except July 1951.

sidered. The cases selected were stratified on the basis of (1) shortest distance between the front and Kansas City, and (2) isallobaric gradient across the front as illustrated in figure 1. This gives a basic stratification (fig. 2) which from table 1 appears to be real.

SUB-STRATIFICATION

It is reasonable that a northerly component of wind in the middle or lower troposphere across the Northern Plains would be conducive to the southward movement of a front in that area. Conversely a southerly component of wind would impede southward movement. After several different indices had been tried, the 700-mb. height difference between Omaha, Nebr., and Ely, Nev., was chosen as an index of meridional flow. A strong southerly component would be reflected in the height at Omaha being much greater than the height at Ely (negative index). Thus, the basic groups were sub-stratified on the basis of this ΔH index (fig. 3).

DEFICIENCY OF ΔH INDEX IN SUB-STRATIFICATION

Figures 2 and 3 in themselves constitute the basic approach used widely in development of objective forecast methods. In this case there is a time lag built into the system.[1] Also in this case (referring to fig. 3), implicit in the use of the ΔH index is the fact that it not only indicates the meridional flow at the synoptic time at which data are taken, but it *also* indicates an assumed characteristic variation in the meridional flow between that synoptic time and the end of the forecast period. This variation might be zero, or of considerable magnitude; it might be known or unknown, but it is implicitly constant for each value of the ΔH index. In the past the fallacy of this assumption of constancy has been recognized, but usually one who devises an objective forecast method has resigned himself to the inclusion of errors inherent in the assumption.

In figure 4 are plotted the once-per-day values of the ΔH index and the 5-day mean ΔH for August 1952, this month having been chosen at random. We see that there is little consistency in the way that the daily ΔH changes from one day to the next when the curve is taken by itself. However, in 24 out of 30 cases, the 24-hour change was *toward the 5-day mean*. This is not at all surprising because of the interdependence of the mean and its components. It does, however, suggest the possibility of using a prognosis of some mean index in enabling us to avoid the assumption mentioned above.

MODIFICATION OF ΔH INDEX

For forecasting purposes, Group 5 yields a sufficiently high probability of frontal passage to be used without further stratification. Similarly Groups 1 and 2 contain a proportion of non-passage cases high enough so that a more complete separation is not necessary. Groups 3 and 4, however, must be considered somewhat indeterminate groups in which further stratification would be useful.

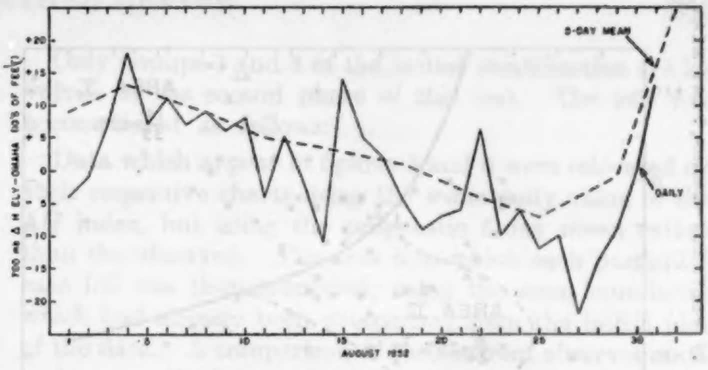

FIGURE 4.—Graph showing variations of the daily 700-mb. ΔH index (Ely minus Omaha), taken from the daily 0300 GMT 700-mb charts, and the mean 5-day 700-mb. ΔH taken from the observed 5-day mean 700-mb. chart and plotted at the middle date of the 5-day period. Data from August 1952, this month having been selected at random.

It has been pointed out that it would be reasonable to assume that modifying the daily ΔH index by the mean 5-day index would permit a more complete separation of the passage from the non-passage cases. This has been done for Groups 3 and 4. The 5-day ΔH index used was taken from the observed 5-day mean 700-mb. chart for the period including the day in question. The mean charts are computed twice weekly for overlapping periods. For cases falling within the overlap, the mean chart used was that whose central date was closest to the date in question. If the case date was equally close to both, the later mean chart was used. The results are figures 5 and 6.

A large negative 5-day mean ΔH index might be interpreted as representing the situation where a "long wave" trough is situated over the western portion of the United States, or even the eastern Pacific, with a relatively large-amplitude ridge downstream. Also, the difference between the daily and the 5-day mean index might, in a broad sense, be interpreted as an indication of the phase relationship between the long-wave and the short-wave patterns. The greater the difference, the greater would be the indicated phase difference.

While the cases in Group 3 (fig. 5) do not fall into distinctive groups, yet it is possible to construct a line of separation (solid line) which divides the sample into two groups of quite different overall passage to non-passage ratios.

Because of sparsity of data in the upper central portion of the chart, the line of separation in this area is uncertain. However, the general area of higher probability of frontal passage (Area I) is in the portion where the ΔH index is favorable for frontal passage and when modified by the 5-day mean index, should remain favorable. In other words, there is a long-wave trough to the east and a long-wave ridge to the west, and the short-wave pattern is not materially out of phase with the long-wave pattern.

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[1] Upper air data are taken from 0300 GMT observations while the "forecast period" ends at 1230 GMT the following day. Thus, the time-lag period for this variable can be as much as 33½ hours.

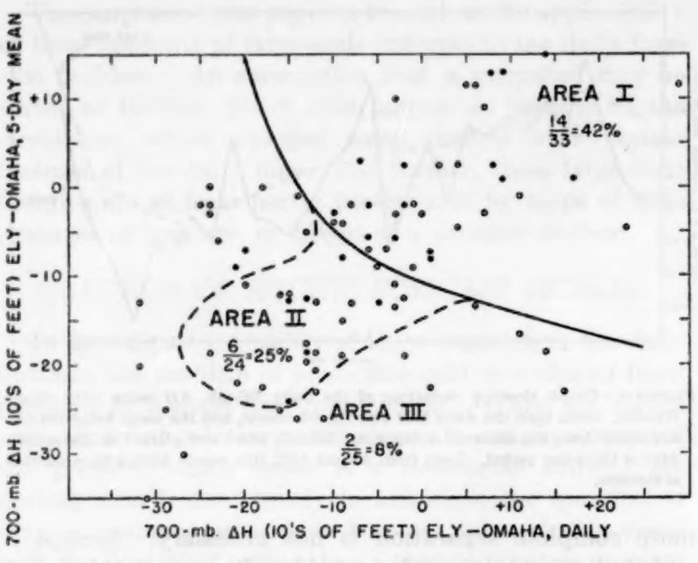

FIGURE 5.—Scatter diagram for Group 3 cases (fig. 3) relating the daily 700-mb. ΔH index (as described in fig. 3) and the 5-day mean 700-mb. ΔH index (Ely minus Omaha on observed 5-day mean 700-mb. chart) to the subsequent passage (●) or non-passage of the front at Kansas City.

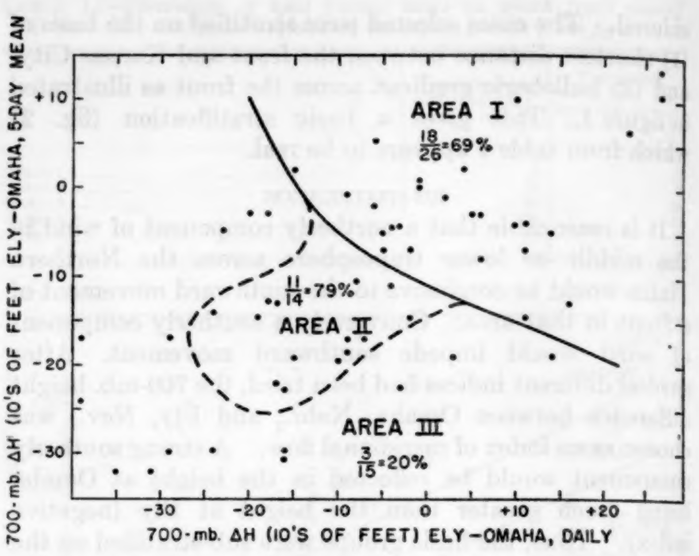

FIGURE 6.—Scatter diagram for Group 4 cases (fig. 3) relating daily 700-mb. ΔH index and 5-day mean 700-mb. ΔH index to subsequent passage (●) or non-passage of front at Kansas City.

In the lower right-hand portion of the chart, although the daily ΔH index is favorable for frontal passage, the 5-day mean index indicates that the daily index is changing toward one less favorable within the time-lag period. Stated in another way, while the distribution of short-wave troughs and ridges appears to be favorable for frontal passage, the long-wave pattern is unfavorable. In that portion of the chart few of the cases are those in which the front passed.

If the same line of separation (solid line) as that determined by the cases in Group 3 is used in Group 4, a separation is achieved, but it is not the best one. Area II in figure 6 contains an even higher proportion of frontal passage cases than Area I. This same area (determined by cases in Group 4) when transposed to Group 3 affords a further separation into a somewhat intermediate proportion of passage to non-passage cases. (See table 2.) Thus it appears that there are three areas, coincident in Group 3 (fig. 5) and Group 4 (fig. 6) each of which contain more or less homogeneous cases.

Area II represents, in terms of the variables, situations in which the daily ΔH index is slightly unfavorable, and when modified by the 5-day mean ΔH, little change is indicated through the time lag period.

TEST

Basically, the aim of tests normally used in connection with an objective method is to determine the degree of homogeneity between two particular samples of data, one sample being the dependent data and the other the independent or test data. Much emphasis is usually placed on the final step or chart if a series of steps or charts is involved. It is generally assumed that if in this final chart or step there appears to be a certain amount of homogeneity between the two groups of data, then validity of all the relationships between the predictor variables and the forecast element is considered demonstrated. But tests that show homogeneity between two independent samples of data at all intermediate steps should be equally valid. In this light, let us briefly consider what has been done thus far:

1. In the initial stratification (fig. 2) homogeneity is demonstrated by an independent test with usual methods, using more cases than were in the dependent group (table 1). On the basis of this test the validity of the stratification is assumed and thereafter both samples are combined.
2. As pointed out earlier, the sub-stratification by means of the daily ΔH only (fig. 3) proves inadequate even without testing.
3. Testing the sub-stratification based on the 5-day mean ΔH index (figs. 5 and 6) involves testing the significance of the deviations of the ratios of Areas I, II, and III from that of its entire Group. Applying a Chi-square test to these deviations yields $\chi^2=21.39$ for 4 degrees of freedom. This means that there is less than one chance out of a hundred that such a distribution of proportions would occur by chance. So the evidence from the Chi-square test is that the distribution is a real one determined by the predictor variables.

From a theoretical standpoint, it is not necessary that like numbered Areas in figures 5 and 6 be coincidental, except under the following conditions: If the data in Groups 3 and 4 are drawn from two populations homogeneous in all respects except their overall passage to non-passage ratios, then the Areas in figures 5 and 6 should be coincidental. This is saying that the marginal variables in figures 5 and 6 (daily and 5-day mean ΔH) contribute alike in Groups 3 and 4. This seems likely, both from theoretical considerations and from the observed ratio distributions in the

two figures, and would merit a test of significance. A χ^2 test may be applied to the deviations from the expected number of passage cases within Group 3, under the assumption that there is homogeneity between like areas in figures 5 and 6 except for the overall difference in ratios. These deviations are determined as follows:

	Group 4	*Group 3*			
			Number passage cases		
	*Ratio**	*Ratio**	*Observed*	*Expected*	*Deviation*
Area I	18/26	14/33	14	(14. 5)	−0. 5
Area II	11/14	6/24	6	(12. 0)	−6. 0
Area III	3/15	2/25	2	(3. 2)	−1. 2
Combined	32/55=.58	22/59=.37			

*Number passage cases/Total number cases.

The calculated value of χ^2 is 3.46 for 2 degrees of freedom. While a test of this sort is not particularly strong support of homogeneity between Groups 3 and 4 except for the overall ratio differences, on the other hand the hypothesis of homogeneity is not disputed.

In summary, as regards the testing of relationships contained in figures 5 and 6, it has been shown:

(1) That the Areas 1, 2, and 3 in both figures 5 and 6 are significantly different from each other.

(2) That there is no evidence against the hypothesis that the combination of the daily and 5-day mean ΔH variables contributes the same in like areas in both figures.

THE PROGNOSTIC 5-DAY MEAN ΔH INDEX

Thus far, the observed rather than the prognostic 5-day mean ΔH has been used for the development of the hypothesis. The usefulness of the hypothesis is limited by the degree to which the ΔH taken from the 5-day mean prognostic 700-mb. chart corresponds to the observed index.

It would appear that a forecast of a 5-day mean index of this sort is an unfair demand to be made upon the mean circulation forecasting technique presently in use. Thus, the question of accuracy of this forecast must be investigated carefully. A simple correlation between the forecast and observed ΔH is certainly pertinent, but in itself gives little indication of its usefulness for our purposes. One could conclude, however, that if the correlation approaches zero, then any further test of usefulness would have little meaning. If a positive correlation is found to exist, then it remains to be shown whether the correlation is high enough to be useful.

For the summer months, June, July, and August, 1947 through 1953, the correlation coefficient between the forecast and observed 5-day mean ΔH is .14 for 178 pairs of data.[2] This appears to be sufficiently high to warrant further investigation of usefulness.

Only Groups 3 and 4 of the initial stratification are involved in the second phase of this test. The test was accomplished as follows:

Data which appear in figures 5 and 6 were relocated on their respective charts using the same daily value of the ΔH index, but using the prognostic 5-day mean rather than the observed. The area into which each particular case fell was then tabulated, using the area boundaries which had already been determined from the initial plot of the data. A comparison of results from observed data and prognostic data is given in table 2.

Table 2.—*Comparative results from figures 5 and 6 using observed 5-day data, and prognostic 5-day data. Ratios are number of frontal passage cases (numerator) and total number of cases together with equivalent percentages.*

	Area I 5-day data		Area II 5-day data		Area III 5-day data	
	Observed	Prognostic	Observed	Prognostic	Observed	Prognostic
Group 3	14/33 42%	14/43 33%	6/24 25%	4/16 25%	2/25 8%	4/20 20%
Group 4	18/26 69%	20/30 67%	11/14 79%	5/7 71%	3/15 20%	6/17 35%

It can be seen from table 2 that the relative percentagewise ranking among the three areas for both Groups 3 and 4 is retained in changing from observed data to prognostic data. Also, the number of cases in each area remains much the same. The most significant difference appears to be the decreased range between the high percentage and the low percentage areas when the prognostic index is substituted for the observed. Since a large range (better separation) is the goal, this change is undesirable. The fact remains that by using prognostic data, even with its errors, a better separation is achieved than was possible in figure 3 without any additional modification.

CONCLUSION

It has been suspected for some time that large-scale and long-period circulation features exert influences on shorter period evolutions of features appearing on synoptic charts. However, up to the present time, no attempt to use this concept systematically or quantitatively has come to the attention of the author. A possible exception is the somewhat qualitative application contained in "Synoptic Weather Types of North America" by the California Institute of Technology, and similar typing systems.

It has been shown in the present paper that it is possible to incorporate into an objective forecast method rather simple measures of these large-scale controls, and thereby add information pertinent to the problem.

It is further demonstrated that there appears to be enough skill in the routinely prepared prognoses of these

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[2] Very nearly significant at the 5% level. ($r_{.05}$ for 200 pairs of data=.14). It is interesting to note that the correlation coefficient for 98 pairs of data from the summers 1947–1950, inclusive, was .09, while for 80 pairs of data from the summers 1951–1953, inclusive, the correlation had increased to .35 suggesting considerable improvement in forecasts insofar as the particular index is concerned.

large-scale features to make these prognoses of use in this particular application. This is particularly true in view of the highly significant correlation between the observed and forecast 5-day mean ΔH for about the second half of the period considered (.35 for 80 pairs of data) in contrast with the first half.

The work done thus far has suggested many avenues for further research. A few of these are:

1. Discovering criteria for the selection of indices which would most effectively specify Grosswetterlage for application to a daily forecast problem.
2. The utility of longer period mean circulation patterns in daily forecasting problems, i. e., 30-day or some other less arbitrary period.
3. The possibility of stratifying both developmental and test data on the basis of Grosswetterlage with the aim of dealing with several homogeneous groups rather than with one heterogeneous group.

ACKNOWLEDGMENTS

The author wishes to acknowledge with thanks the assistance given by the Research Assistant, Miss Norma F. Jarboe, in tabulating data and preparing the figures. Thanks are also due many members of the Staff of the Weather Bureau Airport Station, Kansas City, for their encouragement and helpful suggestions.

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TORNADO-PRESSURE JUMP LINE SITUATION OF MARCH 18, 1954[1]

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[Manuscript received September 27, 1954]

INTRODUCTION

During the late morning and early afternoon of March 18, 1954, an unusually large number of tornadoes occurred in eastern Kansas. These tornadoes were all situated within the observational network of the Severe Local Storms Research Unit, and consequently the pressure pattern associated with these storms could be analyzed in great detail by means of the high-speed microbarographs of the network. These microbarographs are spaced about 30 miles apart, on the average, as can be seen in figure 1.

The purpose of this note is to present a short resumé of a situation that is of particular interest because of the phenomenal agreement between the large number of tornadoes and the pressure jump line that occurred at that time. A more exhaustive case study will be prepared at a later date.

PRESSURE JUMP LINE ANALYSIS

In the course of the routine operations of the Severe Local Storms Research Unit on March 19, 1954, pressure jump reports were gleaned from the weather sequences and were plotted on a chart as in figure 2. On the basis of these 8 pressure jump reports, a preliminary analysis was made of a pressure jump line with isochrones as indicated. Lacking pressure jump reports in Kansas (the network microbarograms are not received until about a month later), but having on hand reports of some of the tornadoes, the pressure jump line was extrapolated backward in time into eastern Kansas. This was done on the basis of the findings in Weather Bureau *Research Report* No. 37 which indicate that a high percentage of severe storms occurred in connection with pressure jump lines.

Later, when the network microbarograms were received, they were analyzed carefully to determine if a pressure jump line existed in the network area on that day. The results of this analysis are presented in figure 1. After the basic data were plotted, isochrones were drawn. It may now be seen that the positions of the extrapolated isochrones of figure 2 agree very well with the actual locations on figure 1.

TORNADOES

On the basis of reports from the Climatological Services Division and notes received from the cooperative observers in the network, the tornadoes were plotted on figure 1 without regard to their location with respect to the isochrones. Of the 15 reported tornadoes, only three did not have a specific location and time of occurrence listed.

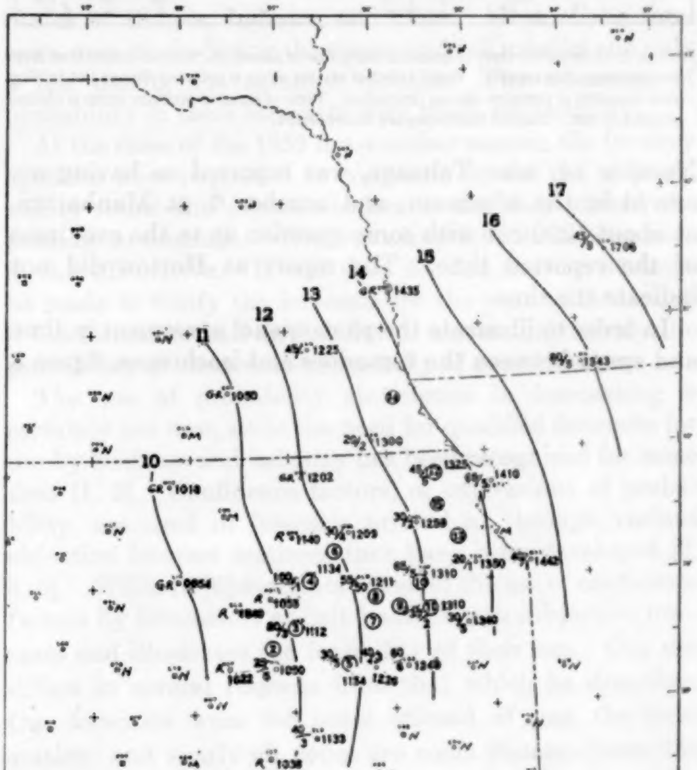

FIGURE 1.—Isochrones (CST) of pressure jump line of March 18, 1954, with tornado locations indicated by encircled numbers. Ratio at left of station circle is pressure change (.001 in. Hg) over duration of pressure change (minutes). Time of onset of pressure jump (CST) is plotted at right. GR represents gradual rise; R, rise; and N, no significant pressure change.

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[1] The research reported on in this paper has been in part sponsored by the Geophysics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command.

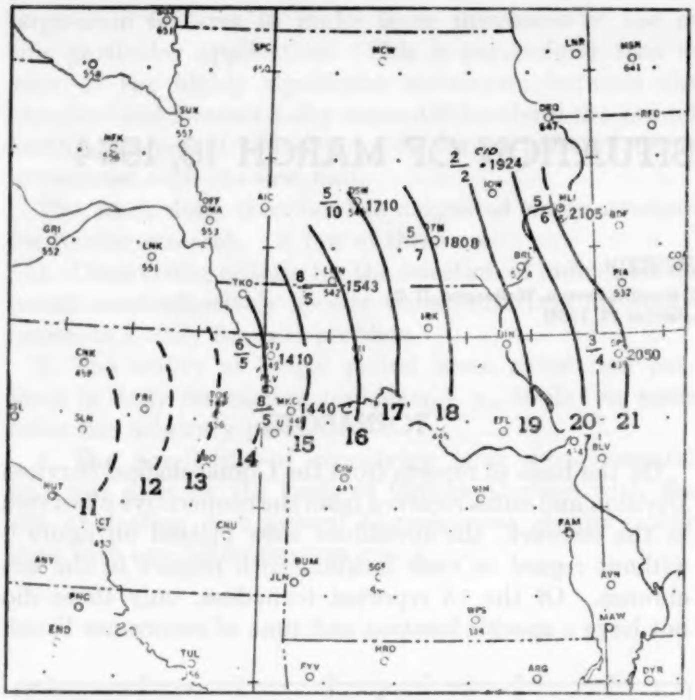

FIGURE 2.—Isochrones (CST) of pressure jump line of March 18, 1954, as determined from weather sequence reports. Ratio to left of station circle is pressure change (.01 in. Hg) over duration of pressure change (minutes). Time of onset of pressure jump is plotted at right in CST. Dashed isochrones are extrapolated.

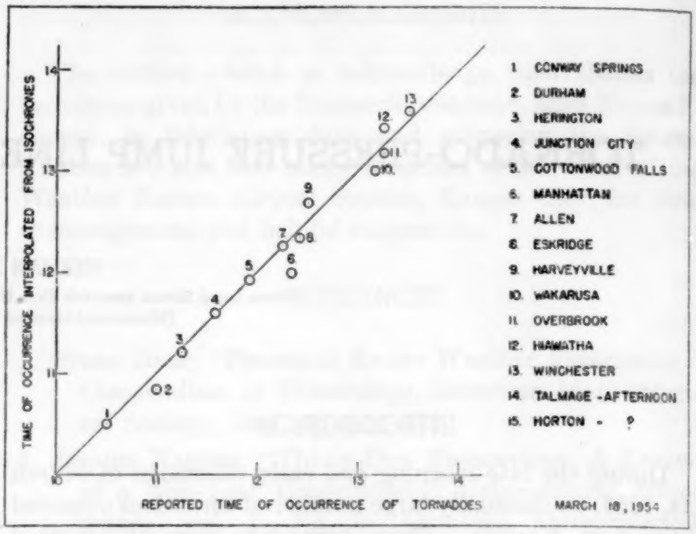

FIGURE 3.—Relationship between reported and interpolated time (CST) of occurrence of tornadoes in Kansas on March 18, 1954.

Number 14, near Talmage, was reported as having occurred in the afternoon, and number 6, at Manhattan, at about 1220 CST with some question as to the exactness of the reported time. The report at Horton did not indicate the time.

In order to illustrate the phenomenal agreement in time and space between the tornadoes and isochrones, figure 3 was prepared. On this diagram, the actual reported times of occurrence of the tornadoes were plotted against the times as interpolated from the isochrone field. Since the same time scale is used for both, the line that represents perfect agreement is a straight line of 45° slope. Note the remarkable fit. The tornado farthest from the line is number 6, and this is one of those whose occurrence time is uncertain.

ACKNOWLEDGMENT

The author is indebted to the members of the Severe Local Storms Research Unit for assistance in the collection and presentation of this material.

VERIFICATION OF "PROBABILITY" FIRE-WEATHER FORECASTS

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[Manuscript received August 5, 1954; revised October 29, 1954]

ABSTRACT

Probability terms, especially in relation to precipitation occurrence, were incorporated in fire-weather forecasts on a trial basis in the Chicago District during the 1952 fire-weather seasons. These forecasts were verified in an attempt to determine whether or not such subjective estimates of probability were feasible. Results show that forecasters have some skill in assessing the probability of the occurrence of precipitation especially for the first 30 hours.

INTRODUCTION

In the job of fire control the forester must make plans and decisions on the basis of weather forecasts. It frequently is helpful to him to know the degree of confidence that the forecaster has in the forecast of some of the weather elements. If, for example, the forecaster made a categorical prediction of rain every time he determined that there was more than a 50 percent chance of occurrence, the forester many times would fail to make the proper presuppression plans. On the other hand, if the forecaster's estimate of the probability of rain is made known to the forester, the latter can weigh his chances of getting rain against the probable consequences if no rain should occur in any particular situation and then determine the presuppression action to be taken.

Uses of probability forecasts in business, industry, agriculture, and aviation have been discussed by Brier [1] and Thompson [2], [3].

Starting in 1952, at the request of the U. S. Forest Service, the Chicago Weather Bureau Forecast Center used probability terms in fire-weather forecasts, particularly with respect to the occurrence of precipitation. The qualifying terms for this purpose were defined as follows:

	Chance of precipitation
Unqualified	approximately 80 to 100 percent.
Probable	approximately 60 to 80 percent.
Possible	approximately 40 to 60 percent.
Chance of	less than 40 percent. (The forecasters state that the lower limit they had in mind when using the term "chance" was about 10 percent.)

Provision was also made for indicating extreme values of minimum humidity or maximum wind velocity that could occur in particular situations by use of the terms "possibly as low as" for relative humidity, and "possibly as high as" for wind velocity. It was understood that the probability of occurrence of the extreme values was considered to be less than 50 percent.

Fire-weather forecasts in this district are made for fire-weather forecast zones of which there are 6 in northern and central Minnesota, 4 in northern and central Wisconsin, 6 in Michigan, and 1 in the southern portion of each of the States of Illinois, Indiana, and Ohio. Most of the forecasts were made during the spring and fall months and only a few during the summer months. The estimates of probability in these forecasts were made subjectively.

At the close of the 1952 fire-weather seasons the forestry agencies were requested to comment on the use of probability terms and advise whether or not they wished the practice to continue. Without exception, the replies were in the affirmative. It was then decided that an attempt be made to verify the forecasts for the year to determine if the forecaster had any ability to assess subjectively the probability of occurrence, especially of precipitation.

The use of probability statements in forecasting is certainly not new, since the need for qualified forecasts for use by business and industry has been recognized for some time [1, 2]. Confidence factors, or expressions of probability, are used in forecasts arrived at through various objective forecast methods that have been developed [2, 4, 5]. Williams [6] describes a trial of the use of confidence factors by forecasters at Salt Lake City in subjective forecasts and illustrates the feasibility of their use. Our use differs in several respects from that which he describes. Our forecasts were for zones instead of just the local station, and nearly all zones are some distance from the forecast center. In addition the top category of his confidence factors was 10, or 100 percent confidence, whereas in our case the unqualified statement was meant to indicate 80 to 100 percent confidence. We did not attempt to state a confidence factor for the no-rain forecasts, though the absence of a qualified rain statement could be interpreted to mean 90 to 100 percent confidence in no rain. In most respects our trial was not as rigidly controlled as was the one Williams describes.

METHOD OF VERIFICATION FOR PRECIPITATION

One of the problems encountered in attempting to verify the forecast lay in the fact that observation periods did not coincide with the forecast periods. The observations from all stations in the fire-weather forecast zones were used, including regular fire-weather stations and all Interstate Airway Communications Stations (INSACS) and Weather Bureau station observations which are plotted on our 6-hourly district maps. By definition, the fire-weather forecast periods are as follows:

Tonight	time of release to sunrise tomorrow (time of release 1:30–2:00 p. m. CST)
Tomorrow	sunrise to sunset tomorrow
Next day	sunset tomorrow to sunset the next day

Precipitation measurements at Weather Bureau and INSAC stations are, of course, taken at 0030 CST and each 6 hours thereafter. Precipitation measurements at fire-weather stations are taken once daily for a 24-hour period ending at 0800 CST. Where times of beginning and ending were indicated there was little difficulty, but perhaps as many as half of the fire-weather stations did not indicate the times.

To resolve the problem of time periods, the fire-weather forecast periods were considered as follows: "tonight" was considered as 1830 CST to 0630 CST, "tomorrow" as 0630 CST to 1830 CST, and "next day" as 1830 CST tomorrow to 1830 CST the next day. This no doubt caused some loss, especially on the period "tonight", but was thought to be the best way of proceeding. The precipitation measurements at INSAC and Weather Bureau stations for these periods were taken from the 6-hourly district maps. Where fire-weather stations had indicated the times of beginning and ending, the precipitation could be placed in the proper period. In those cases where the time was not indicated, the precipitation was placed in the proper period as accurately as possible by careful inspection of the 6-hourly district maps. At the time of carrying out this operation, the forecast for the period was not known so that there could be no bias in favor of the forecast.

In verifying precipitation, a trace was considered as "no rain", since in fire-weather usage it is disregarded on the danger meter. The number of reporting stations in each fire-weather forecast zone in most cases was three to five, but varied from one to eight. If 0.01 in. or more of precipitation was reported in the period at one or more of the stations in the zone, it verified a "rain" forecast and broke a "no rain" forecast. All forecasts calling for showers, even though "scattered" or "widely scattered", were classed as "rain" forecasts.

From the above it will be noted that there could be no instances where the verification worked "both ways," that is verified either a "rain" or "no rain" forecast. In this respect, the verification is much more rigid than that used for our local and state forecasts.

Table 1.—*Verification of "rain" forecasts, Chicago district fire-weather forecast zones, 1952, seasons*

	Unqualified	Probable	Possible	Chance
Tonight				
Number of forecasts	342	41	29	38
Percentage of periods with rain reported	67.3	63.4	44.8	13.2
Tomorrow				
Number of forecasts	228	43	55	43
Percentage of periods with rain reported	49.1	58.1	41.8	16.3
Next day				
Number of forecasts	117	80	156	47
Percentage of periods with rain reported	55.6	56.3	36.5	27.7

RESULTS

Table 1 gives the verification figures for the "rain" forecasts for the three forecast periods.

Certainly the verification figures are lower than one would like to have them, but, nevertheless, it appears as though the forecasters have some ability to assess the probability of the occurrence of precipitation. This ability is greatest for the first period and decreases as the time period is extended. The only figures that do not agree in general are for the unqualified and probable forecasts for "tomorrow," and for this there is no apparent explanation. It should be noted, however, that for the "tonight" and "tomorrow" forecasts there are many times as many in the unqualified classification as in any other. This is at least partly due to the fact that on 1 day per week and during periods when the fire-weather supervisor was on inspection trips or on a district shift, the forecasts were made by one of a number of forecasters other than the fire-weather supervisor. Since many of these forecasters made fire-weather forecasts only infrequently, they were not as prone to use the qualifying terms as was the fire-weather forecaster. It is quite certain that if a real attempt had been made to assess the probabilities with every forecast, there would have been fewer forecasts in the unqualified category and more with qualifying terms. This should have resulted in better verification for the unqualified forecasts and perhaps poorer verification for the other groups.

Table 2 gives the verification of all "rain" forecasts combined without respect to the assigned probability, and excluding "chance." The "chance" forecast cannot be considered a "rain" forecast since by definition we are indicating less than 40 percent chance of rain.

Table 2.—*Verification of all "rain" forecasts combined without respect to assigned probability and excluding "chance," Chicago district fire-weather forecast zones, 1952 seasons*

	Tonight	Tomorrow	Next day
Number of forecasts	412	326	353
Percentage of periods with rain reported	65.3	49.1	47.3

TABLE 3.—*Verification of "no rain" forecasts, Chicago district fire-weather forecast zones, 1952 seasons*

	Tonight	Tomorrow	Next day
Number of forecasts	1,347	1,428	1,397
Percent correct	85.7	84.6	65.8

To provide a more complete picture, the "no rain" forecasts for the 1952 fire-weather seasons were also verified. These results are given in table 3. From the results it is apparent that even on "fair" forecasts the verification drops off abruptly as the forecast is extended into the third day.

The verification shows that there is little distinction between the "chance" forecasts and the "no rain" forecasts, and between the "rain" forecasts and the "rain probable" forecasts. Combining them, but keeping the "rain possible" forecasts separate from the others, the results given in table 4 were obtained.

TABLE 4.—*Verification of "rain" (unqualified and probable), "rain possible," and "no rain" (chance and no rain) forecasts, Chicago district fire-weather forecast zones, 1952 seasons*

	Rain forecast	Rain possible	No rain forecast	Total
Tonight				
Rain observed	256	13	197	466
No rain observed	127	16	1,188	1,331
Total	383	29	1,385	1,797
Percent correct	66.8		85.8	
Tomorrow				
Rain observed	137	23	227	387
No rain observed	134	32	1,244	1,410
Total	271	55	1,471	1,797
Percent correct	50.6		84.6	
Next day				
Rain observed	110	57	491	658
No rain observed	87	99	953	1,139
Total	197	156	1,444	1,797
Percent correct	55.8		66.0	

The skill scores for all forecasts, with "chance" again verified as "no rain," are given in table 5. The skill for forecasting precipitation the third day ahead is low compared to the first two periods. Perhaps the only excuse for routinely making a forecast for the third day lies in the fact that the forecaster has an opportunity to attempt to correct the third day's forecast on the second day. Very likely in portions of the country where weather changes are less frequent than in this district, verification for the third day is better. Even in this district on occasion the weather regime is such that a forecast can be made with a rather high degree of confidence for three, or even four, days ahead. But this cannot be done routinely. The only important criticisms of fire-weather forecasts heard in this district have concerned the forecast for the third day.

TABLE 5.—*Skill scores for all forecasts, with "chance" verified as "no rain," Chicago district fire-weather forecast zones, 1952 seasons*

	Tonight	Tomorrow	Next day
Skill score	.488	.314	.101

HUMIDITY VERIFICATION

There were only a few cases in which the term "possibly as low as" was used in connection with minimum humidity predictions in the fire-weather forecasts for 1952. When used, it was in a manner such as this—"Humidity tomorrow 30–40 but possibly as low as 20–30." In verifying humidities, certain problems are encountered since the minimum humidities are not observed. Instead, readings are taken at 0800, 1200 and 1630 CST. In attempting to judge the forecasts, the lowest humidity at any station in the forecast zone at any observation during the day was used. The results are given in table 6.

TABLE 6.—*Verification of qualified humidity forecasts, Chicago district fire-weather forecast zones, 1952 seasons*

Forecast %	Number of forecasts	Number of times lowest observed humidities were in ranges			
20–30 but possibly as low as 10–20 (or 15)	36	*10–19* 3	*20–29* 24	*30 or higher* 9	
30–40 but possibly as low as 20–30	32	*10–19* 5	*20–29* 9	*30–39* 14	*40 or higher* 4
40–50 but possibly as low as 30–40	17	*20–29* 1	*30–39* 2	*40–49* 2	*50 or higher* 12

CONCLUSIONS

From the verification of fire-weather forecasts for the 1952 seasons it is believed the following conclusions can be drawn regarding probability terms:

1. The forecasters show some skill in assessing the probability of the occurrence of precipitation especially for the periods "tonight" and "tomorrow." It is felt therefore, that forecasters are justified in continuing the practice.
2. Probability terms should be used even more frequently than they were during this test period. An unqualified forecast of precipitation should be made only in cases of extremely high confidence.
3. The forecasters have little skill in forecasting precipitation for the third day ahead. Therefore nearly all precipitation forecasts for that day should contain a qualifying term. The prediction for the third day should be termed an "outlook" rather than a "forecast." The suggestion has also been made that, especially when the timing of precipitation is uncertain, a longer period such as an outlook for the third and fourth day be used.
4. Because of the small number of times that a probability phrase was used in the humidity forecast, no definite conclusions can be drawn. The practice, nevertheless, is being continued.

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THE WEATHER AND CIRCULATION OF SEPTEMBER 1954[1]

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PERSISTENCE OF SUMMER CIRCULATION THROUGH SEPTEMBER 1954

A conspicuous feature of the mid-tropospheric circulation for the month of September 1954 was its similarity over the Western Hemisphere to the mean circulation for the summer season of 1954. The persistence of many features of the circulation and weather during the individual months of this summer has previously been noted [1, 2]. Comparison of figures 1 and 2 shows that this summertime persistence carried on into September to a remarkable degree. Over the region from the central Pacific eastward to western Europe the troughs and ridges during September (fig. 1) were located in very nearly the same longitudinal positions as they were during the summer (fig. 2). Likewise the fields of 700-mb. height anomaly for summer and September were rather highly correlated over this area. In fact, over a limited region covering the United States and the adjacent western Atlantic,[2] the correlation coefficient between the fields of 700-mb. height anomaly for summer and September 1954 was +.52. There are no comparable coefficients available for other years, but the average one-month lag correlation for August-September for the same area during a period of 18 years was about +.30 [3]. For strict comparison the correlation coefficient for August-September 1954 was also computed and its value was +.62. Thus, it is safe to conclude that September's circulation exhibited more persistence from previous months than is usually found at this time of year. Furthermore, visual inspection of all mean 700-mb. charts for summer and September revealed that no other year in the entire period of record (back to 1933) exhibited anywhere near the degree of persistence observed this year over the Western Hemisphere. The unusually stable nature of this circulation pattern in roughly one-half of the Northern Hemisphere, while the circulation over the other half underwent relatively well-marked changes, suggests that thermodynamic factors (i. e., the effects of differential heating over continents and oceans) may play a major role in such cases of persistence.

CIRCULATION FEATURES OF SEPTEMBER 1954 IN RELATION TO WEATHER OVER THE UNITED STATES

The circulation feature most directly associated with United States weather during September 1954 was the zonally-oriented continental ridge which covered the southern two-thirds of the United States (fig. 1). Under this broad mean ridge, in which height anomalies were all positive, above-normal surface temperatures prevailed (Chart I-B). Note that a pronounced belt of temperatures in excess of 4° F. above normal roughly paralleled the axis of maximum positive height anomaly at 700 mb. (fig. 1). In this zone during the first week of the month some unusually high daily temperature readings for September were registered. For instance, it was 103° F. at Kansas City, Mo. on the 2d; 105° F. at Fort Smith, Ark. on the 3d; 104° F. at St. Louis, Mo. on the 4th; 105° F. at Nashville, Tenn. on the 5th; 105° F. at Shelbyville, Ky. on the 6th, and 103° F. at Richmond, Va. on the 7th.

As is usually the case in the warmer season over the United States, hot weather was accompanied by little rainfall over much of the area dominated by the continental anticyclone aloft (Chart III). Note that the southern half of the country under this ridge was free of cyclones (Chart X) and had comparatively few fronts (fig. 3). As a result, rather severe drought conditions persisted through September over much of Texas, Oklahoma, the Carolinas, Georgia, and Alabama. These States were comparatively dry throughout the entire summer (cf. fig. 1B of [2]) and have been generally deficient in precipitation for the past few years.

Significant breaks in the drought situation occurred this month in large portions of Louisiana, Mississippi, Tennessee, and Kentucky (Chart III). Heavier-than-normal rainfall in the first two of these States was related to the development of a mean easterly wave at 700 mb. in the northern Gulf of Mexico where easterly flow was stronger than normal (fig. 1). As is typical of easterly waves on daily or shorter-period charts, precipitation occurred on the east side of the trough line. Heavier-than-normal precipitation over Kentucky and Tennessee showed little relation to the mean circulation. Most of

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[1] See Charts I-XV following p. 279 for analyzed climatological data for the month.

[2] Latitudes 30° to 50° N., longitudes 50° to 125° W.

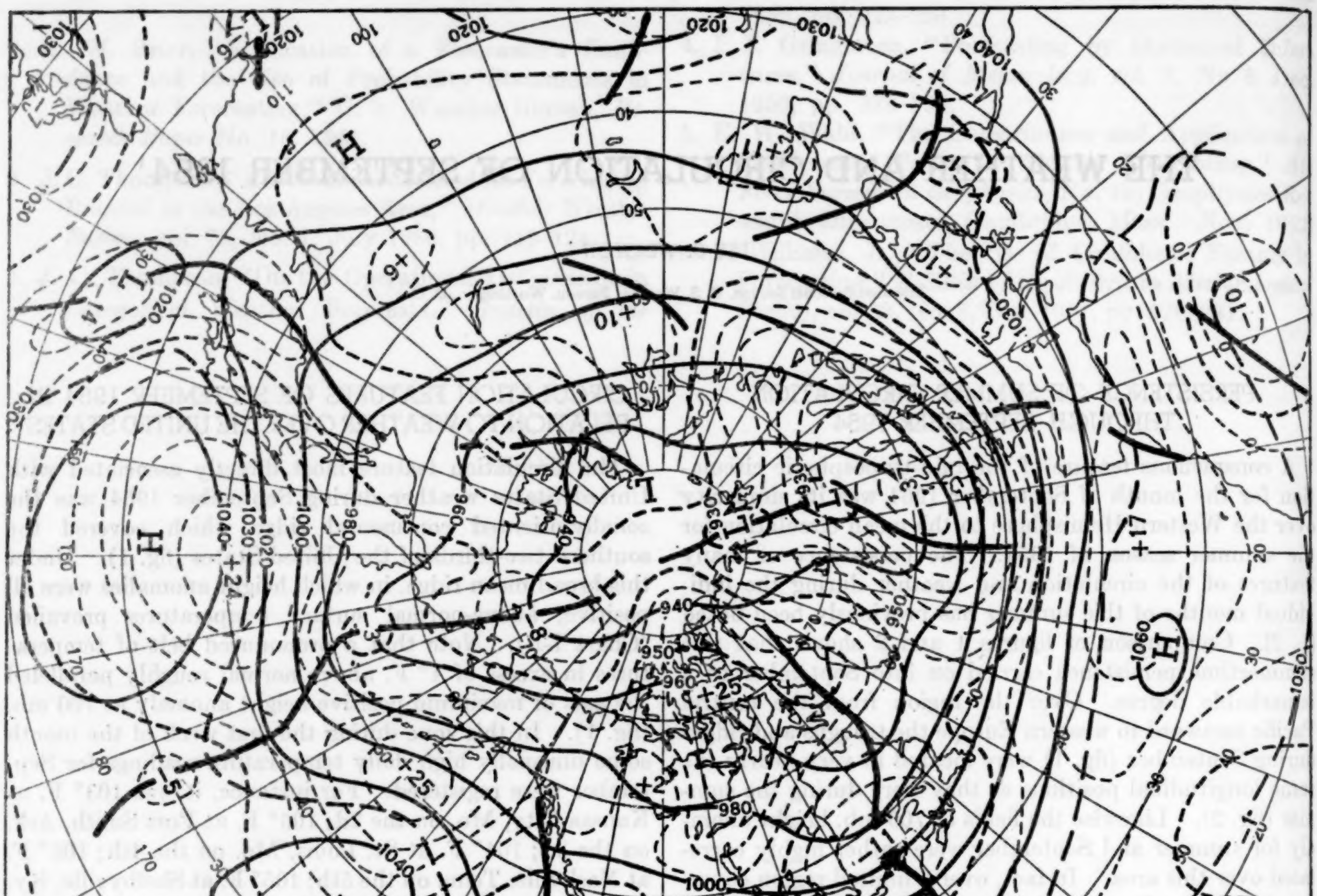

FIGURE 1.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for August 31–September 29, 1954. Wave pattern over Western Hemisphere was very similar to prevailing pattern of summer of 1954 (fig. 2). For United States area major circulation feature was extensive anticyclonic circulation in southern portion.

this substantial precipitation occurred within a few days around the 20th when the passage of a well-defined daily trough and accompanying cold front and squall lines brought heavy showers to the area.

In Arizona, Utah, eastern Nevada, and northwestern Colorado precipitation was also in excess of normal (Chart III). This was associated with moisture transported from the Gulf of Mexico around the southwestern and western peripheries of the mean continental ridge (fig. 1). Inspection of daily and 5-day mean 700-mb. charts indicates that much of this precipitation occurred when a trough or Low center moved into the area from the prevailing trough off the west coast, thereby providing a mechanism for widespread shower activity. These troughs also brought several thrusts of cool Pacific air into the Far West so that surface temperatures over that area were generally somewhat below normal (Chart I-B).

The mean trough in eastern North America (fig. 1) had some important direct influence on the weather over the Northeast and along much of the immediate Atlantic coastal strip during September. Since the trough was deeper than normal mainly in its middle-latitude section, surface temperatures in the East were cooler than normal only in New England, New York, and northern New

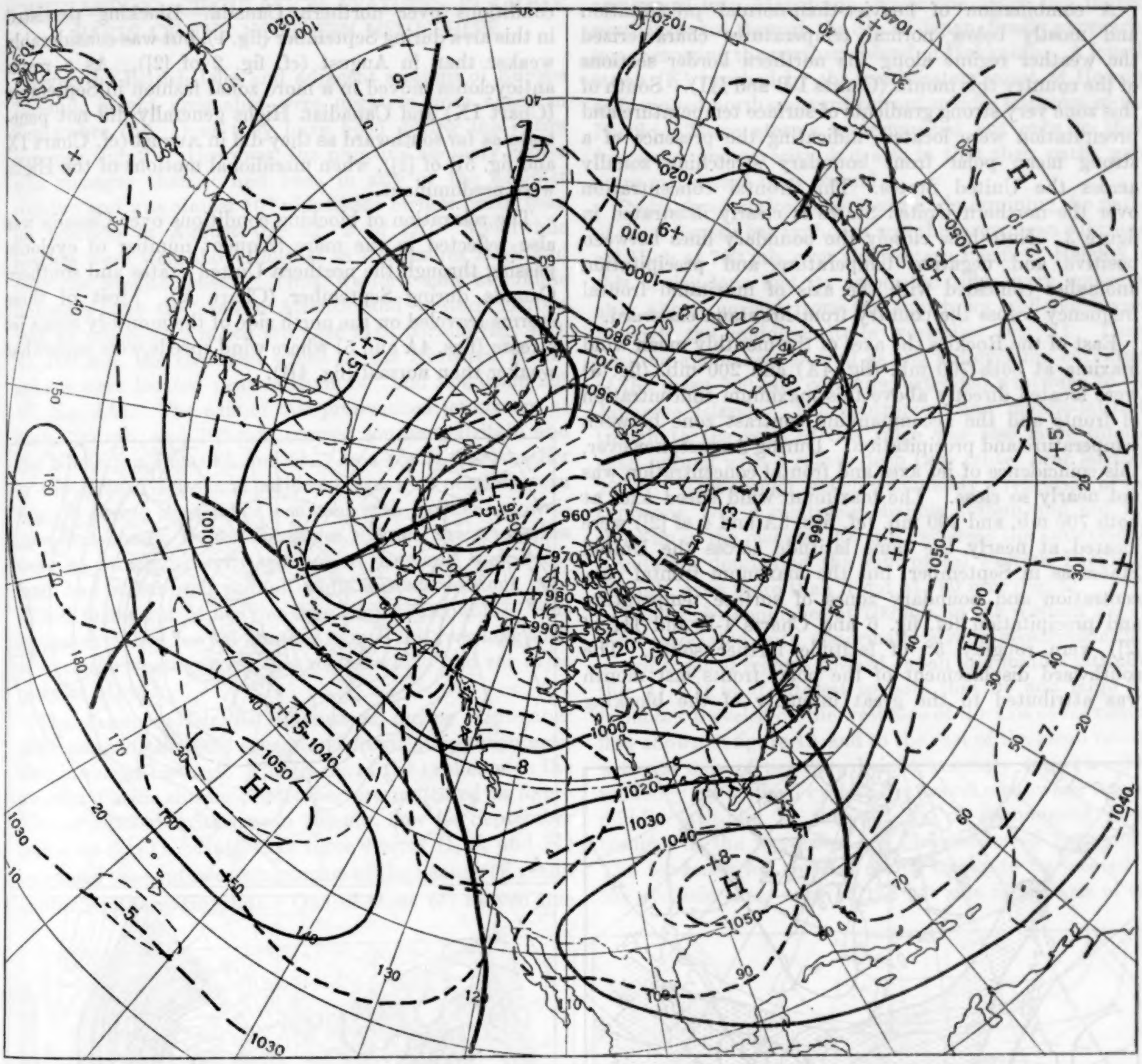

FIGURE 2.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for summer 1954. Month-to-month persistence of many circulation features during the season makes this chart very representative of the prevailing circulation of the summer. Comparison with figure 1 indicates that persistence continued through September over the Western Hemisphere.

Jersey (Chart I-B), where heights aloft were below normal. Farther south stronger-than-normal westerly flow and the proximity of the continental anticyclone aloft allowed warm weather to dominate the coastal region.

Precipitation over New England and the Atlantic coastal strip was heavier than normal for September largely as a result of the rainfall associated with hurricane Edna which moved north-northeastward close to the coast on the 10th and 11th (Chart X). The path of this storm between the Bahamas and New England lay within a few degrees of latitude of the position of the monthly mean trough (fig. 1). This storm's pronounced meridional motion was associated with a marked increase in amplitude of the long-wave trough along the east coast as the cyclone came out of the subtropics. Its large-scale evolution in this sense was somewhat akin to that of the hurricane of September 1938 [4] and of hurricane Carol which battered the New England coast on the last day of August 1954 [2]. Details of the case history of Edna are given in an article in this issue by Malkin and Holzworth [5].

A combination of heavier-than-normal precipitation and mostly below normal temperatures characterized the weather regime along the northern border sections of the country this month (Charts I-B and III). South of this zone very strong gradients of surface temperature and precipitation were located, indicating the presence of a strong mean polar front boundary stretching zonally across the United States. This frontal concentration over the northern United States is clearly illustrated in figure 3. Note how closely the boundary lines between positive and negative temperature and precipitation anomalies coincided with the axis of maximum frontal frequency across the country from Montana eastward.

East of the Rockies the axes of the monthly mean wind maxima at both 700 mb. (fig. 4A) and 200 mb. (fig. 5) were located directly above this maximum concentration of fronts and the accompanying contrast zone between temperature and precipitation. During August, however, this coincidence of jet axes and frontal concentration was not nearly so close. The maximum wind speed axes at both 700 mb. and 200 mb. (cf. figs. 3A and 4 of [2]) were located at nearly the same latitude across the United States as in September, but the maximum frontal concentration and boundary zones of surface temperature and precipitation (cf. fig. 6 and Charts I-B and III of [2]) were roughly 5° of latitude farther south. The southward displacement of the polar fronts last month was attributed to the great intensity of the blocking conditions over northern Canada. Blocking persisted in this area during September (fig. 1), but was considerably weaker than in August (cf. fig. 2 of [2]). As a result anticyclones moved in a more zonal fashion in September (Chart IX) and Canadian Highs generally did not penetrate as far southward as they did in August (cf. Chart IX and fig. 5B of [2]), when meridional motions of the Highs were predominant.

The relaxation of blocking conditions over Canada was also reflected in the more frequent number of cyclones passing through the northern United States and southern Canada during September (Chart X). Most of these storms traveled on the north side of the monthly mean jet stream (figs. 4A and 5) where wind speeds were somewhat weaker than normal (fig. 4B).

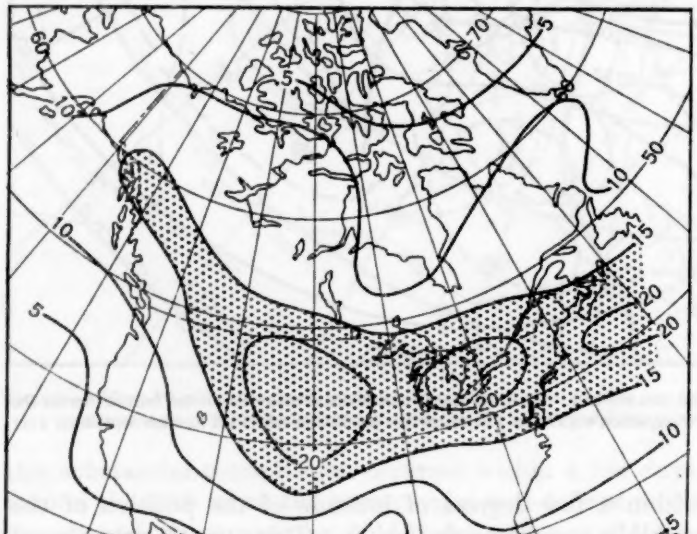

FIGURE 3.—Number of days in September 1954 with surface fronts of any type (within squares with sides approximately 500 miles). Frontal positions taken from *Daily Weather Map*, 1:30 p. m. EST. Sharp contrasts in temperature and precipitation regimes (see Charts I-B and III) existed across the zonal axis of maximum frontal frequency in northern portion of the United States. Fronts were less frequent in southern United States which was dominated by the continental ridge aloft (fig. 1).

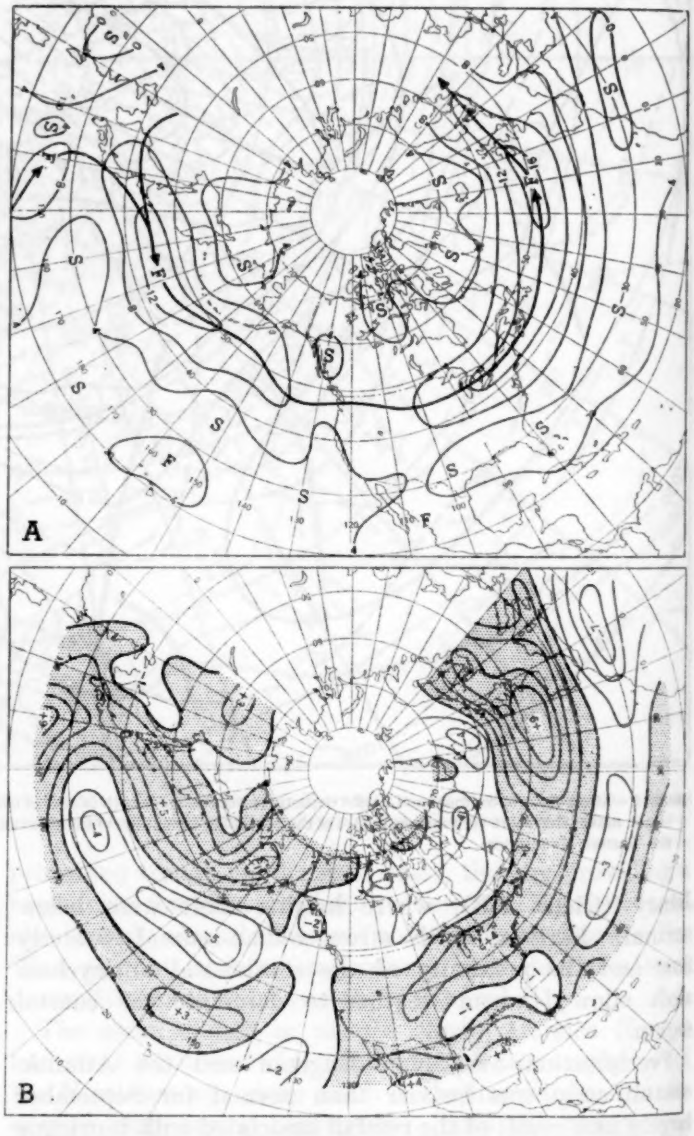

FIGURE 4.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for August 31–September 29, 1954. Solid arrows indicate major axes of maximum flow. Axis of maximum flow across North America extended zonally through northern United States nearly coinciding with axis of maximum frontal frequency shown in figure 3. Strongest flow on map was located in eastern Atlantic where mean winds of 16 m/sec were 9 m/sec above normal.

OUTSTANDING CIRCULATION FEATURES IN OTHER PARTS OF THE NORTHERN HEMISPHERE

Over the British Isles and adjacent sections of Europe 700-mb. height anomalies were negative once again in September (fig. 1) as they have been during the entire summer (fig. 2). However, the negative anomaly center was stronger than it had been in any of the summer months and was almost 10° of latitude farther north than its position in August (cf. fig. 2 of [2]). Meanwhile heights were well above normal in the Azores High and over the Mediterranean. Thus, westerly flow at middle latitudes over the eastern Atlantic and western Europe was as much as 9 m/sec stronger than normal (fig. 4B). At 700 mb. the strongest winds in the Northern Hemisphere were located near latitude 50° and longitude 20° W. (fig. 4A). The axis of this pronounced jet stream at both 700 mb. and 200 mb. crossed southern Britain and the North Sea (figs. 4A and 5). As a result, the weather in the British Isles and adjacent areas of northwestern Europe during September was cool with frequent storminess and many frontal passages. Since the westerlies were so strong, eastern sections of England and Scotland had subnormal rainfall while western sections continued to experience heavier-than-normal amounts. This regime extended for yet another month the very long spell of cyclonic weather over this region which had set in as early as May.

The Japanese Islands experienced during September 1954 some of the most severe and frequent typhoon activity in recent history. The tracks of the typhoons in the western Pacific during September are indicated in figure 6 superimposed on the mean 700-mb. flow for September (same as fig. 1). Note that three storms (I, J, and M) traversed the southwestern portion of the Islands (Kyushu and/or southern Honshu). One of these (J) moved due northward into Manchuria, while the other two moved northeastward through the Sea of Japan, finally approaching or crossing the northern island of Hokkaido. A fourth storm (K) brushed by the southeastern coast of Honshu as it moved northeastward toward middle latitudes of the Pacific. These storms were unusual not only in their frequency and severity, but also in that their paths were more meridional than normal.

Probably of major importance in determining the paths of these September typhoons was the large mean subtropical High at 700 mb. over the western Pacific. Heights in this anticyclone and its associated ridge were considerably above normal from the subtropics well northward through the middle-latitude westerlies (fig. 1). These positive anomalies, as well as the anticyclonic curvature of the mean 700-mb. contours, extended westward to the Japanese Islands. The subtropical and middle-latitude trough to the west of this ridge was also more intense than normal with a rather deep Low center near latitude 25° N. This trough, which was mainly a reflection of the typhoons, was a relatively shallow system and did not show up in the mean at 200 mb., whereas the anticyclonic circulation dominated the subtropical western Pacific at 200 mb. even more than it did at 700 mb. (fig. 5).

The height anomalies at 700 mb. in the western Pacific were associated with abnormally strong geostrophic flow out of tropical regions toward Japan and middle latitudes (fig. 4). It is of interest to note that by and large the typhoons traveled on the west side of the axis of maximum flow shown in figure 4A and to the east of the mean trough with its axis of negative height anomaly (fig. 1). The tendency for tropical cyclones to travel northward toward middle latitudes in the vicinity of pronounced mean troughs in the westerlies has been observed frequently. The tendency for tropical storm tracks to be located in the cyclonic shear zone on the left side of the axis of the

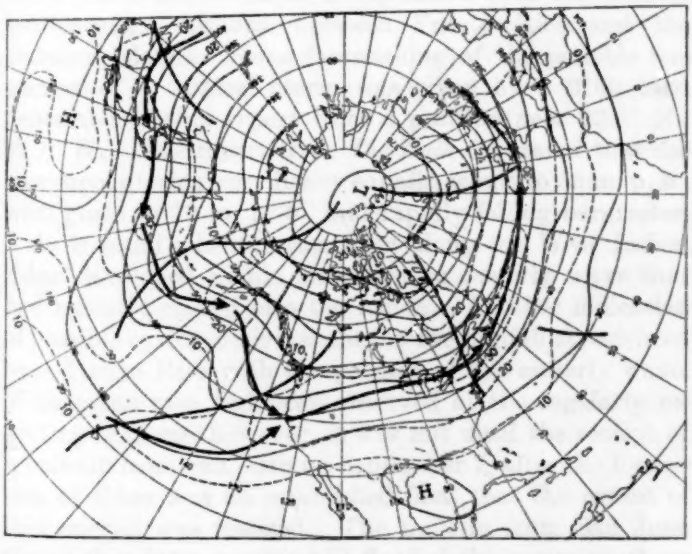

FIGURE 5.—Mean 200-mb. contours (in hundreds of feet) and isotachs (dashed, in meters per second) for August 31–September 29, 1954. Solid arrows indicate the axes of monthly mean jet streams. Circulation pattern and jet axes are very similar to 700-mb. features of figures 1 and 4A, except over eastern Pacific.

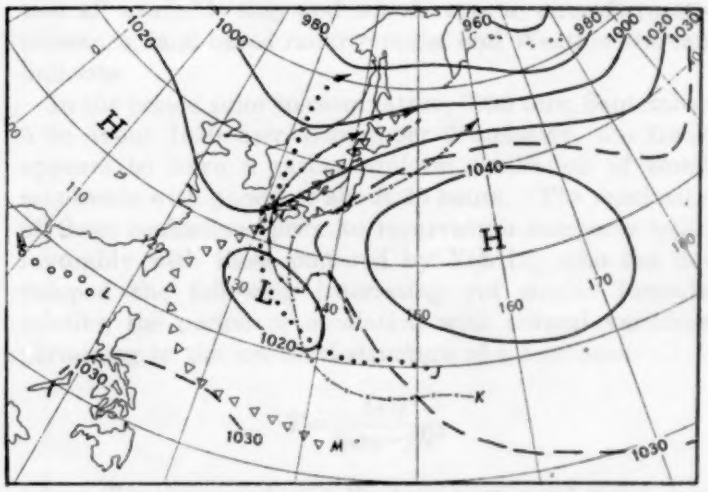

FIGURE 6.—Tracks of typhoons in western Pacific during September 1954 superimposed on mean 700-mb. contours (same as in fig. 1). Letters at beginnings of tracks are first letters of officially designated names of Pacific typhoons. Alphabetical order represents chronology of typhoon occurrence. Four of the five typhoons affected the Japanese Islands, taking a large toll of lives and property. Unusual frequency of typhoon tracks in far westerly position over Japan was associated with abnormally strong upper anticyclone in western Pacific. (See anomalies of 700-mb. height in fig. 1.)

mean current at 700 mb. is not so well established, but it has been frequently noted in this series of articles that major extratropical storm tracks are often so located with respect to mean westerly jet streams.

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HURRICANE EDNA, 1954

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INTRODUCTION

Hurricane Edna was the second tropical storm of 1954 to penetrate the east coast of the United States, the center reaching into New England on September 11, some 11 days after Hurricane Carol. While total loss of life and damage to property for Edna were less than for Carol, the tracks were similar. A reexamination of some of the meteorological conditions associated with the formation and movement of Edna may reasonably be expected to have elements in common with other storms of similar life history. Coincidentally, while this article was being written, Hurricane Hazel, about one month after Edna, moved inland across the South Carolina coast on October 15, and accelerated northward, maintaining exceptional intensity for a tropical storm moving over land. Although Edna was the least spectacular of the three hurricanes, its occurrence in September calls for it to receive most of the authors' attention as a contribution to the review of September's weather. Only incidental references are made to Carol and Hazel.

THE FORMATION OF EDNA

The first surface indication of an apparently closed circulation that subsequently evolved into Hurricane Edna was noted the night of September 5, in the extreme southwestern Atlantic between Puerto Rico and the Bahama Islands. Some forewarning of the possible formation of a tropical storm was given by a 2100 GMT, September 5 ship report from a position near 22.5° N., 67.7° W. This report from *The Bulk Oil* stated that she was encountering very heavy squalls, winds to 50 m. p. h., with gusts to 70 m. p. h., and rapidly falling barometer.

As is usual when storms form along the West Indies, Edna developed within an extensive easterly wave that had recently moved into the region. Another indication of possible cyclogenesis was the intense rainfall experienced over Puerto Rico with the passage of the easterly wave. Widespread rain had been observed at the regularly reporting stations; however, it was not until the receipt of a bulletin from San Juan on September 7, after the formation of Edna was an established fact, that the extent of this rainfall was realized. The bulletin from San Juan stated that intense rains had flooded the entire southern and western coastal sections of the Island, some stations reporting more than 4 inches of rain in a 24-hour period, while other sections had more than 10 inches during a 2-day period. With respect to convective rain, at any rate, the easterly wave within which Edna formed, showed exceptional activity in the day or so prior to formation of the storm.

Several ship reports on the surface chart for 0030 GMT, September 6, gave more positive indications that a tropical storm was developing in the region just northeast of Santo Domingo. At this time the center was located at 21.6° N., 68.5° W. While the winds had not yet reached hurricane force, the first advisories at that time predicted intensification.

THE TRACK OF EDNA

Prior to 1830 GMT, September 6, ship reports in the immediate vicinity of the storm were sparse, and therefore the positions shown for the storm track (fig. 1), in this time interval, should be viewed with some skepticism. Likewise, the loops shown in the track, while based on a careful consideration of the few reports available at the time, are not certain features, except with respect to very slow movement of the center at the respective positions. The final track, as pictured in figure 1, takes into consideration all available ship and island reports, aircraft reconnaissance, land-based radar reports, and Weather Bureau bulletins.

In the period prior to recurvature, 0030 GMT, September 6 to about 1830 GMT, September 9 inclusive, the track appears to have a rather uniform oscillation of small amplitude with period of about 26 hours. The regularity of these oscillations prior to recurvature compares quite favorably with those pictured by Yeh [1], who has developed the following interesting yet simple formula relating the period of oscillation with several variables pertaining to the low level structure of a hurricane:

$$T=\frac{4\pi R^2}{2v_0r_0-fR^2}$$

where T is the period, v_0 is the maximum wind speed, r_0 is the distance from the center to v_0, f is the Coriolis parameter and R is the radius over which air is assumed to move

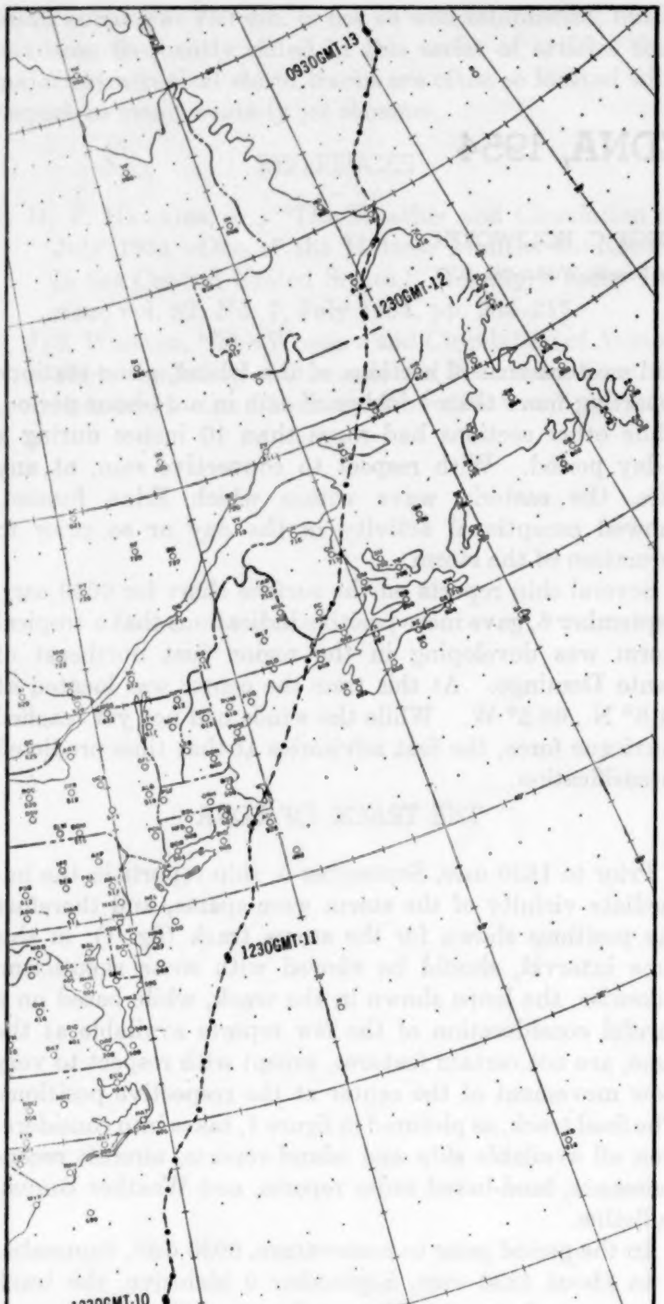
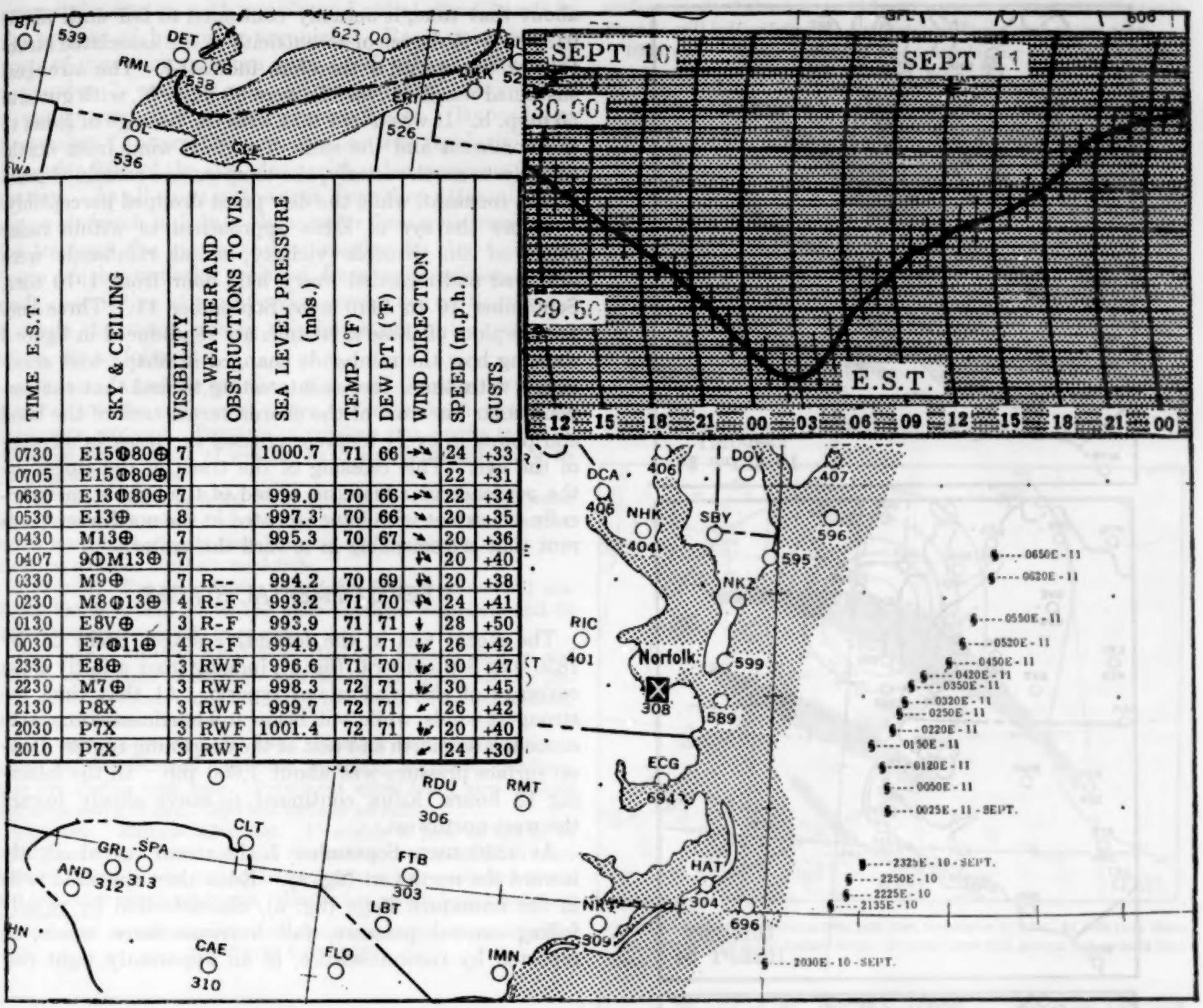


FIGURE 1.—The track of Edna, shown in 3-hourly intervals.

with the vortex. As the 26-hour period of oscillation in the 3-day interval was judged to be accurate to within 10, and possibly 5 percent, T, the period, was used as one of the "knowns" in making a trial substitution into Yeh's equation. For the maximum wind, the value of 120 m. p. h., from the *Fairland* in the forward semicircle, agreed quite well with the report of maximum wind slightly over 100 knots received from reconnaissance. Also, along this portion of the track, a reasonably accurate estimate for the diameter of the eye, obtained by averaging the values from a number of reconnaissance reports, was 25 miles. With the eye itself having a radius of just over 10 miles, a compromise between several reports on the extent of the region with maximum winds indicated that a total distance of 25 miles out from the center was a reasonable estimate for the radius distance to the maximum winds. Substitution into Yeh's formula, using 0.6×10^{-4} sec.$^{-1}$ for the Coriolis parameter, gives about 95 miles for the value of R, which result may be looked upon as the radius of the storm. This value was considered to be of the right order of magnitude. However, in working further with the equation, it soon became apparent, as recognized by Yeh [1], that even for a small storm, much more detailed observational data than now currently available would be required to test or apply the relationships involved. In attempting to solve for the period, several trial computations have indicated that only small changes in the other variables, within present limits of observation, lead to large differences in the resulting period. The equation is very sensitive to v_0, r_0, and R, such that there is little hope, at present, of applying the formula with expectations of specific and consistent results.

Soon after 1230 GMT, September 9 and until about 2130 GMT of the same day, aircraft reconnaissance radar reports became confusing. For example, the center was at times reported to be stationary, followed by a report indicating a sudden displacement southeastward; still a later report again mentioned stationary, and subsequently another indicated a sudden northeastward movement. A careful post-analysis indicates that some of the reports were inconsistent. It has been shown that errors in interpretation of radar echoes have occurred [2], and some may be due to the fact that the beam picks up the nearest squall band which may blot out possible echoes from behind the band. Occasionally, false eyes have been encountered [3], as proven by instances when the mistakes were subsequently discovered by the reconnaissance aircraft while in flight, and corrected messages sent. This happened at least twice during the reconnaissance of Edna.

Some of the difficulties and disappointments in accurately locating the eye of a storm may be caused by the eye often being in a state of flux, and, in particular, frequently possessing an isolated and centrally located cloud [4] of variable size, such that, to an aircraft in flight, the central cloud bank may visually blend in with the true outer cloud walls of the eye. It is therefore apparent that a storm track such as ours of Edna, does not begin to re-



TIME E.S.T.	SKY & CEILING	VISIBILITY	WEATHER AND OBSTRUCTIONS TO VIS.	SEA LEVEL PRESSURE (mbs.)	TEMP. (°F)	DEW PT. (°F)	WIND DIRECTION	SPEED (m.p.h.)	GUSTS
0730	E15⦶80⊕	7		1000.7	71	66	↘	24	+33
0705	E15⦶80⊕	7					↘	22	+31
0630	E13⦶80⊕	7		999.0	70	66	↘	22	+34
0530	E13⊕	8		997.3	70	66	↘	20	+35
0430	M13⊕	7		995.3	70	67	↘	20	+36
0407	9⦶M13⊕	7					↘	20	+40
0330	M9⊕	7	R--	994.2	70	69	↘	20	+38
0230	M8⦶13⊕	4	R-F	993.2	71	70	↘	24	+41
0130	E8V⊕	3	R-F	993.9	71	71	↓	28	+50
0030	E7⦶11⊕	4	R-F	994.9	71	71	↙	26	+42
2330	E8⊕	3	RWF	996.6	71	70	↙	30	+47
2230	M7⊕	3	RWF	998.3	72	71	↙	30	+45
2130	P8X	3	RWF	999.7	72	71	↙	26	+42
2030	P7X	3	RWF	1001.4	72	71	↙	20	+40
2010	P7X	3	RWF				↙	24	+30

FIGURE 2.—Composite chart showing barograph trace from Norfolk, Va., radar reports from the same vicinity, and simultaneous surface observations from Norfolk.

veal the smaller scale, but nonetheless significant, variations in eye structure and relative position.

While the report by Gutenberg [5] concerning the usefulness of microseisms in tracking hurricanes is encouraging, the authors have not given attention to this aspect of Edna, based on information from Kammer [6] and Dinger [7], that the microseismic technique for the tracking of tropical storms is no longer looked upon with as much enthusiasm as several years ago. Among the reasons given for this change of opinion is doubt that the signal is generated in the immediate vicinity of the hurricane; it is thought rather that the energy is introduced into the earth by some type of wave action at variable and considerable distances from the storm.

LAND-BASED RADAR REPORTS ALONG EDNA'S TRACK

Radar reports from the vicinity of Norfolk, Va., and records of synoptic reports from Norfolk itself, describe vividly the sequence of weather as Edna approached these stations from the south-southwest and passed about 120 miles to the east on a track to the north-northeast. Figure 2 is a composite, which includes the detailed track of Edna as determined by radar from this vicinity. The barograph trace and surface observations in the figure are from Norfolk.

The radar reports show that at 0150 EST, September 11, the eye of Edna was closest to Norfolk. The barograph trace shows that although pressure began to level off at

about that time, it actually continued to fall until about 0230 EST. A degree of eccentricity in the associated structure of the storm is therefore indicated. The strongest sustained winds at Norfolk were 30 m. p. h., with gusts to 50 m. p. h. It was noted that with the passage of Edna to the northeast and the shift of surface wind from northeasterly to northwesterly, the temperature remained practically constant, while the dew point dropped perceptibly.

Before the eye of Edna approached to within radar range of the Norfolk vicinity, spiral rainbands were observed and recorded every half hour from 1910 GMT, September 10 to 0110 GMT, September 11. Three successive plots of these rainbands are reproduced in figure 3 showing how the rainbands changed in shape and orientation with time. It was interesting to find that the perpendicular bisectors of the chords across each of the band end points in every instance crossed the track in advance of the eye. This crossing of the track of the storm, by the perpendicular bisector, ahead of the eye, is geometrically consistent with bands located in the northwest quadrant that are spiralling in toward the center.

DEVELOPMENTAL STAGES

The storm was in the formative stage (Riehl [2]) by 1830 GMT September 6, (fig. 4), judging from a fairly dense coverage of ship and island reports. At that time, the strongest winds, while still below full hurricane force, were concentrated north and east of the deepening center. Lowest surface pressure was about 1,000 mb. In the following 18 hours, Edna continued to move slowly toward the west-northwest.

At 1830 GMT, September 7 the storm veered slightly toward the northwest (fig. 1). Edna then appeared to be in the immature stage (fig. 5), characterized by rapidly falling central pressure, full hurricane-force winds, as reported by reconnaissance, in an apparently tight ring

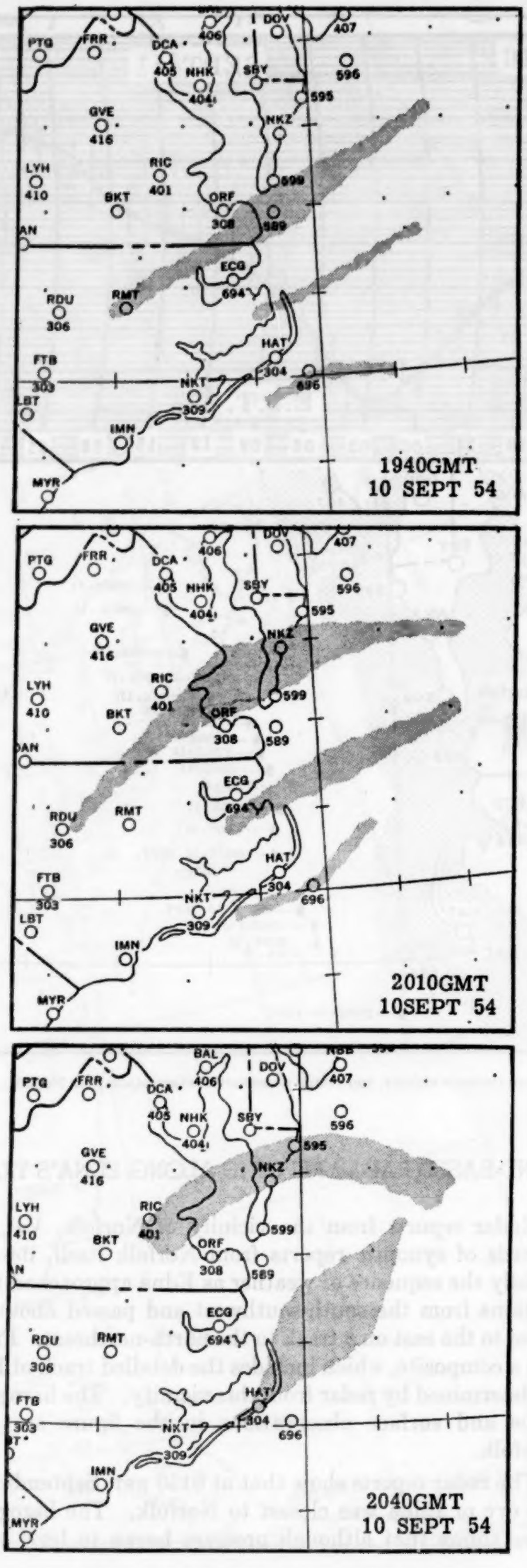


FIGURE 3.—Plot of radar echoes as observed from the Norfolk, Va. area, showing the rapidity with which spiral bands change shape and size.

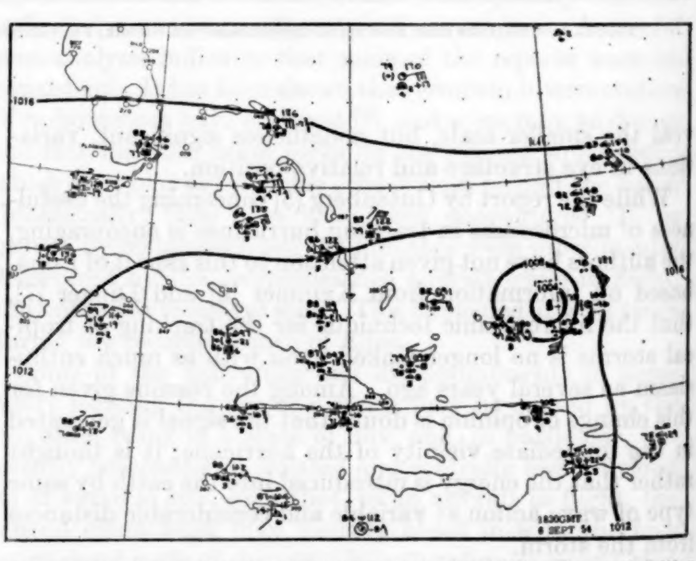


FIGURE 4.—Surface weather chart for 1830 GMT, September 6, 1954. The usual plotting model was used, except visibilities were omitted. At this time Edna was considered to be in the formative stage.

around the center, with squalls and spiral cloud bands in the process of becoming organized. Reconnaissance reports of minimum pressure gave 1,001 mb. at 1430 GMT, September 7, and 992 mb., 5½ hours later. As yet, the storm covered only a relatively small area. By mid-day September 7, aircraft reconnaissance was regularly sending radar fixes of the eye, along with other pertinent information. As all ships in the area were then attempting to give wide berth to Edna,[1] these radar fixes were invaluable for tracking the storm and estimating its development. Some of the remarks received from reconnaissance aircraft, descriptive of conditions near the eye on September 8, while the storm was in this immature but developing stage, are as follows:

0330 GMT. Altitude 8,000 feet. Eye position is center of 20 mile diameter hole [in radar echo] to sea. Weather band pattern on radar very confused. Positions in previous two reports based on horseshoe shape at end of weather band and believed in error by 25 miles too far north.

0430 GMT. Altitude 8,000 feet. Eye is circular hole [in radar echo] to sea, 20 miles diameter, fix believed accurate. Weather bands intensified slightly past hour but do not clearly define eye. Heaviest weather northern semicircle.

0530 GMT. Eye now fairly well defined by weather and sea. Squall bands extend 80 to 100 miles northern semicircle and 70 miles southern semicircle from eye.

0630 GMT. Altitude 8,000 feet. Definite increase in size and number of weather bands, now well developed spiral, equally [developed] in northeast quadrant during past hour. Eye well defined, circular, 20 miles diameter.

0730 GMT. Altitude 8,000 feet. Weather increased slightly in extent and intensity all quadrants, especially northwest quadrant near eye during past hour. Prominent spiral band now extends 140 miles north of eye. Eye will defined on radar.

0900 GMT. Altitude 8,000 feet. Now able to pick up eye at 90 miles [from eye]. Previously had to run in to within 30 to 40 miles [of eye]. Squalls now extend 100 miles from eye south semicircle and 150 miles north semicircle. Radar sea return [echo] indicates surface winds of about 80 to 90 knots near eye in northern semicircle. Squalls still intensifying all quadrants. Departing storm area.

1000 GMT. Radar indicates Edna developing rapidly. Lost eye at 150 miles [from eye].

A portion from one of the surface maps during the interval when Edna was in the mature stage, is shown in figure 6. From all indications, the central pressure had stopped falling, while simultaneously, the circulation had been expanding and the radius of hurricane-force winds had increased. Scarcity of data precludes positive verification that the storm lost symmetry and that the area of bad weather had extended itself farther to the right of the motion than to the left, both of the above features being typical of the mature stage.

Edna had little effect on continental United States until several hours after 1830 GMT, September 9. It was then that the storm accelerated almost directly northward in

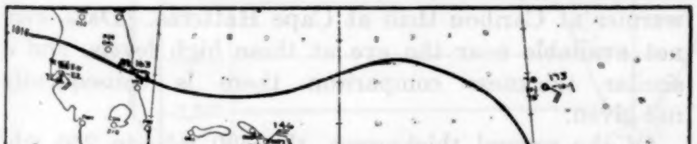


Figure 5.—Surface weather chart for 1830 GMT, September 7, 1954. At this time Edna was believed to be in the immature stage.

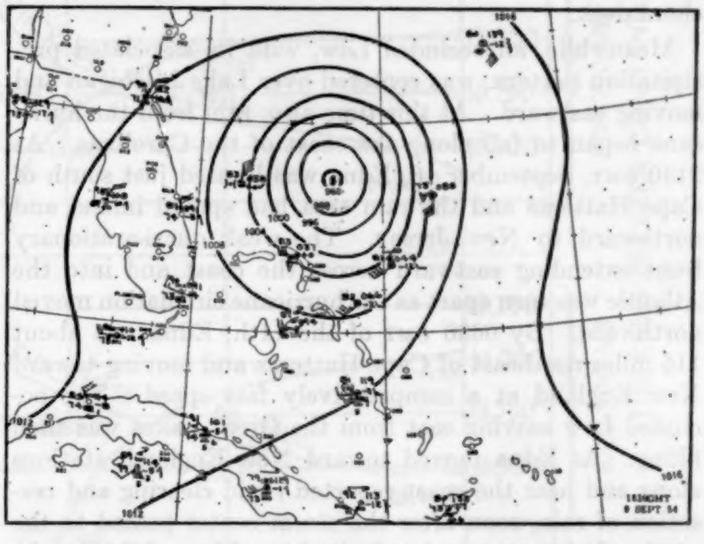


Figure 6.—Surface weather chart for 1830 GMT, September 9, 1954. At this time Edna was believed to be in the mature stage. To avoid crowding, several isobars have been omitted.

Figure 7.—Surface weather chart for 1830 GMT, September 11, 1954.

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[1] One ship, the *Fairland*, was caught in the eye and was seen from the reconnaissance aircraft flying in the eye [4].

the general direction of Cape Hatteras. Stations on the southeastern seaboard began to report rapidly increasing cloudiness. A weak quasi-stationary surface front extended eastward along the southern Tennessee border to South Carolina and thence northeastward into the Atlantic, but there was little weather associated with this diffuse front. As the hurricane progressed northward, the onshore winds increased in speed and the cloudiness spread inland from the Carolinas through Pennsylvania. The Appalachian Mountains and the quasi-stationary front with its cooler air to the north, served as a barrier, promoting upslope motion, thereby increasing the cloud cover. Over New England, the flow was also onshore due to the presence of a ridge of high pressure to the northeast, which accounted for the cloudiness that already existed there. By 0630 GMT, September 10, all States on the Atlantic coast north of the Carolinas were covered by a continuous cloud deck.

Meanwhile, an occluded Low, with its associated precipitation pattern, was centered over Lake Michigan and moving eastward. At this time also, rain from the hurricane began to fall along the coast of the Carolinas. At 2130 GMT, September 10, Edna was located just south of Cape Hatteras and the rain area had spread inland and northward to New Jersey. The weak quasi-stationary front extending eastward across the coast and into the Atlantic was torn apart as the hurricane circulation moved northward. By 0630 GMT of the 11th, Edna was about 115 miles northeast of Cape Hatteras and moving toward New England at a comparatively fast speed. The occluded Low moving east from the Great Lakes was then filling. As Edna moved toward New England, stations along and near the coast reported rapid clearing and cessation of rain, soon after the storm center passed to the north of their respective latitudes. Meanwhile, in the New England area, the rains had intensified to a steady downpour and the winds had increased to gale force with frequent strong gusts. At 0030 GMT, September 12, Edna was centered just a few miles west of Eastport, Maine, having passed directly over Cape Cod. Soon thereafter, communications in the area were disrupted, and it was difficult to accurately determine the position of the storm. Continued rapid northeastward movement was subsequently verified.

Definite criteria are not available to fix the time at which Edna became extratropical or entered into the decaying stage. As the storm moved away from New England, it followed the trough along a cold front into a Low to the north (see fig. 7) a sequence of events which is known to forecasters to be conducive to only slow decrease in intensity. Other symptoms of the decaying stage that are considered to be typical include decrease in size after recurvature and upon entering the westerlies, and loss of tropical characteristics while becoming extratropical. After moving up through Canada, Edna, then an extratropical storm, passed into the Atlantic on a track toward the east.

ASPECTS OF THE VERTICAL STRUCTURE

Figure 8 is a space cross section through the eye of Edna, showing constant pressure and thickness profiles. The dropsonde in the eye was released at 700 mb., and the sounding extrapolated up to 125 mb., taking into consideration mean eye values shown by Riehl [2]. This extrapolated portion of the sounding may be somewhat too cold in the region just above 700 mb. Over the eye, the tropopause was considered to lie above 125 mb. At the time of the cross section, Edna was centered just southwest of Nantucket and moving toward an extratropical Low located to the north in Canada. While Edna was still of tropical structure, she was now in the vicinity of an upper cold Low, and subject to modifications from this source as well as from the extratropical air now enveloping the area at the surface.

If thicknesses are chosen for constant pressure surfaces such that these constant pressures are always in the same ratio, then from hydrostatic considerations, equal thicknesses will have the same mean virtual temperature. The constant pressure surfaces in figure 8 were selected with this relationship in mind. The height and thickness profiles illustrate that the low central pressure (946 mb.) was not counterbalanced by the warm core, even to 125 mb., there being some trace of gradient cyclonic flow even at this level. At Cape Hatteras, N. C., the tropopause was at 93 mb., and at Caribou, Maine, it was located at 145 mb. Large differences in temperature of the lower stratosphere were associated with the change in slope of the 62.5-mb surface. For while the 125-mb. level was 440 feet lower at Caribou than at Cape Hatteras, the 62.5-mb. level was 100 feet higher at Caribou. So the layer 125 mb. to 62.5 mb. was 540 feet thicker at Caribou than at Cape Hatteras. Since for thicknesses whose constant pressure surfaces are in the ratio of 2:1, a difference of 200 feet equals a difference in temperature of 3° C., the layer 125 mb. to 62.5 mb. was about 8.1° C. warmer at Caribou than at Cape Hatteras. Data were not available near the eye at these high levels, and a similar thickness comparison there is consequently not given.

Of the several thicknesses, the 500 mb. to 250 mb. stratum showed the greatest thickness variation between the eye and the two stations at the extremities of the cross section. From figure 8, the variation in thickness for this stratum between Cape Hatteras and the eye was 740 feet (about 11.0° C.), while the variation in thickness of the stratum between the eye and Caribou was 900 feet (about 13.4° C.). Some of this 900-foot variation was related to the cold Low situated to the north of Caribou.

It can be seen from figure 8 that the strongest gradients in the constant pressure profiles occurred near the eye of the hurricane, where the strongest winds were observed. The gradient decreased with altitude, and the winds likewise. Thus, the thermal winds around the eye were anticyclonic, and this agrees with the structure of a warm core Low.

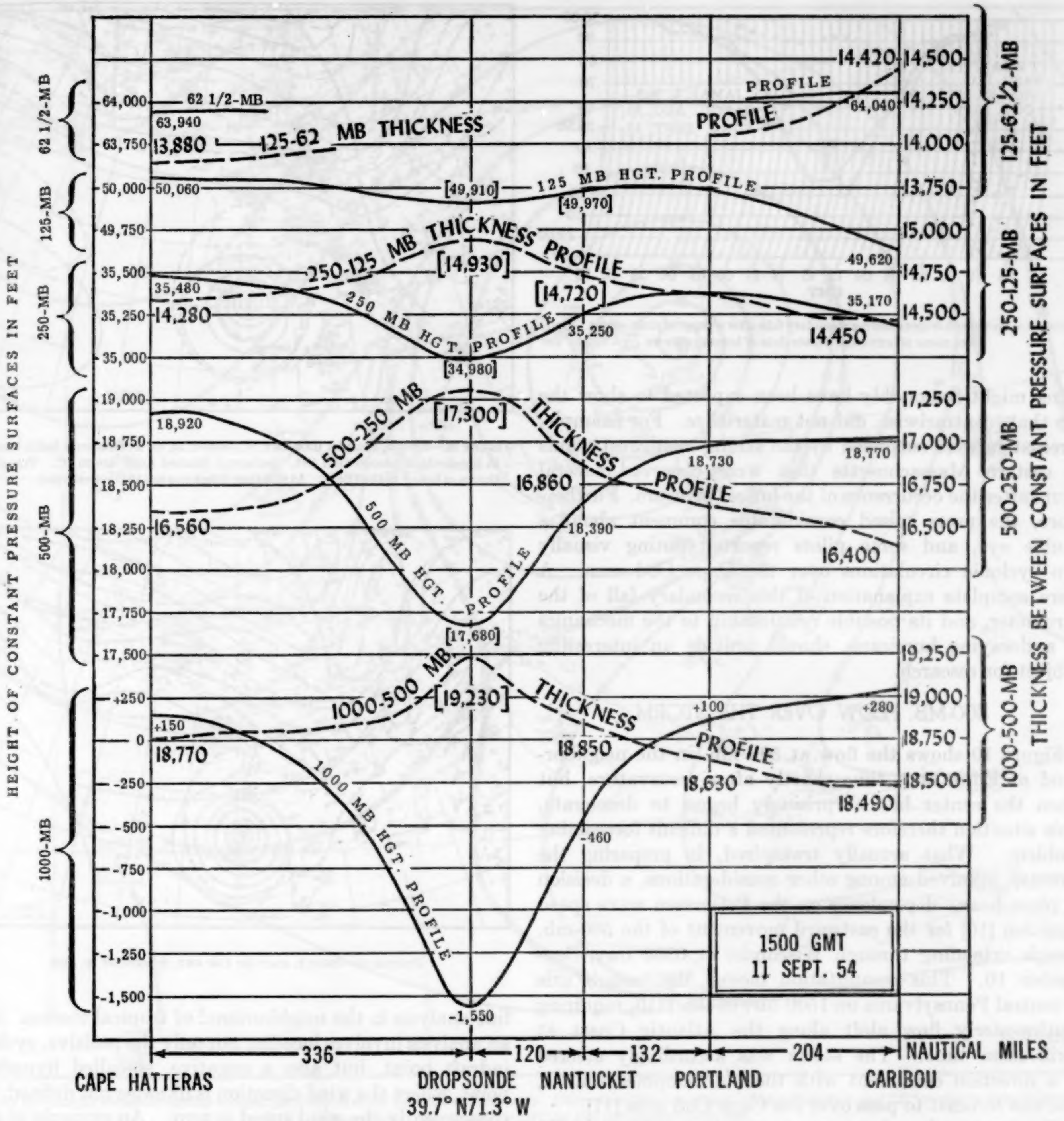

FIGURE 8.—Cross section for 1500 GMT, September 11, 1954, through the eye of Edna. The dropsonde was made in the eye. Heights of constant pressure surfaces are shown as dashed lines. Figures over stations are height and thickness values. Brackets indicate approximations.

SECONDARY DIP IN BAROGRAM

In figure 9, selected barograph traces from hurricanes Carol and Hazel have been superimposed over that of Edna. The secondary dip, not present with Edna, is a distinct and surprising feature in the traces of the other two. These secondary pressure troughs are astonishingly like the dip shown by Pierce [8] on the barograms of the New England hurricane of September 21, 1938. All traces examined indicate the duration of falling pressure to be about 15 minutes.

The explanation of the dip offered by Pierce [8] was the presence of another cyclonic circulation within the main storm. If so, this would be in contrast to the known instances of tornado type vortices embedded within hurricanes, which to this date, have only been observed in the forward semicircle of the advancing tropical storm [9]. Several meteorological conditions associated with

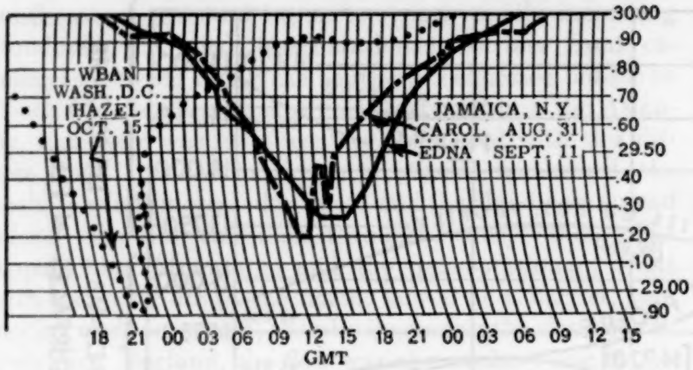

FIGURE 9.—Barograph traces showing secondary falls after passage of main center. Dates after name of hurricane denote date of lowest pressure.

Edna might reasonably have been expected to show the dip that, contrariwise, did not materialize. For example, forecasters were surprised by the strong northwest winds in eastern Massachusetts that were observed several hours after the occurrence of the lowest pressure. Furthermore, the press raised considerable comment about a double eye, and some pilots reported noting visually two cyclonic circulations over the Cape Cod area. A more complete explanation of this secondary fall of the barometer, and its possible relationship to the mechanics of a decaying hurricane, should provide an interesting subject for research.

500-MB. FLOW OVER THE STORM

Figure 10 shows the flow at 500 mb. in the neighborhood of Edna at a time shortly after recurvature, but when the center had surprisingly begun to decelerate. This situation therefore represented a difficult forecasting problem. What actually transpired, in preparing the forecast, involved among other considerations, a decision to place heavy dependence on the Petterssen wave speed equation [10] for the eastward movement of the 500-mb. trough extending through Wisconsin at 0300 GMT, September 10. This computation moved the trough axis to central Pennsylvania on 1500 GMT of the 11th, requiring southwesterly flow aloft along the Atlantic Coast at verification time. The storm was accordingly steered in a direction consistent with these developments aloft, and was forecast to pass over the Cape Cod area [11].

The forecast based on upper air information available 12 hours later, 1500 GMT, September 10 (fig. 11), was slightly less perplexing, in that the trough was advancing at a uniform speed, and the hurricane center, by 1830 GMT of the 11th, was again accelerating northward, thereby increasing the probability of Edna being "picked up" by the trough aloft.

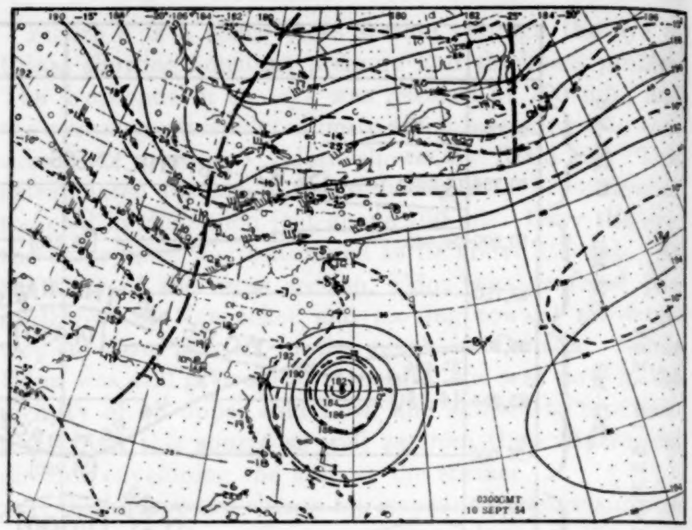

FIGURE 10.—500-mb, chart for 0300 GMT, September 10, 1954. Contours (solid lines) are in hundreds of geopotential feet. Isotherms (dashed lines) are in °C. Troughs are shown as heavy dashed lines. At this time Edna was not in the westerlies.

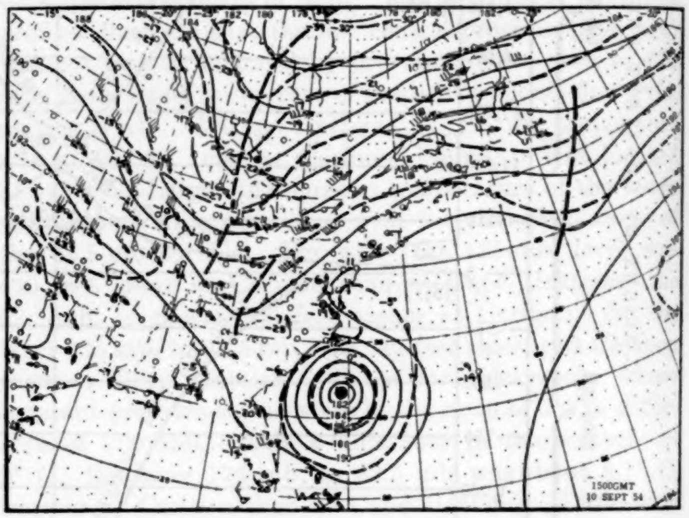

FIGURE 11.—500-mb. chart for 1500 GMT, September 10, 1954.

SURFACE STREAMLINE ANALYSIS

Further interest has recently been aroused by Sherman and Carino [12] and Sherman [13] in the advantages of definitely locating singular points when performing streamline analysis in the neighborhood of tropical storms. Such an analysis involves locating not only the positive, cyclonic indraft point, but also a negative, so-called hyperbolic point, where the wind direction is likewise not defined, and consequently the wind speed is zero. An example of such an analysis is shown in figure 12. Several diagrammatic views of flow and streamline analyses involving hurricanes, vividly protraying the hyperbolic point, have been prepared by Wobus [14]. The hyperbolic and cyclonic-indraft points are supposed to be related to the embedding current. One such relationship involves the orientation of the hyperbolic point from the storm center. The point is frequently located in the left forward quadrant of a tropical storm, and if rapid changes in orientation occur, recurvature may be anticipated even while more positive indications are still lacking. It may therefore be appropriate to relate briefly some of the results of such an

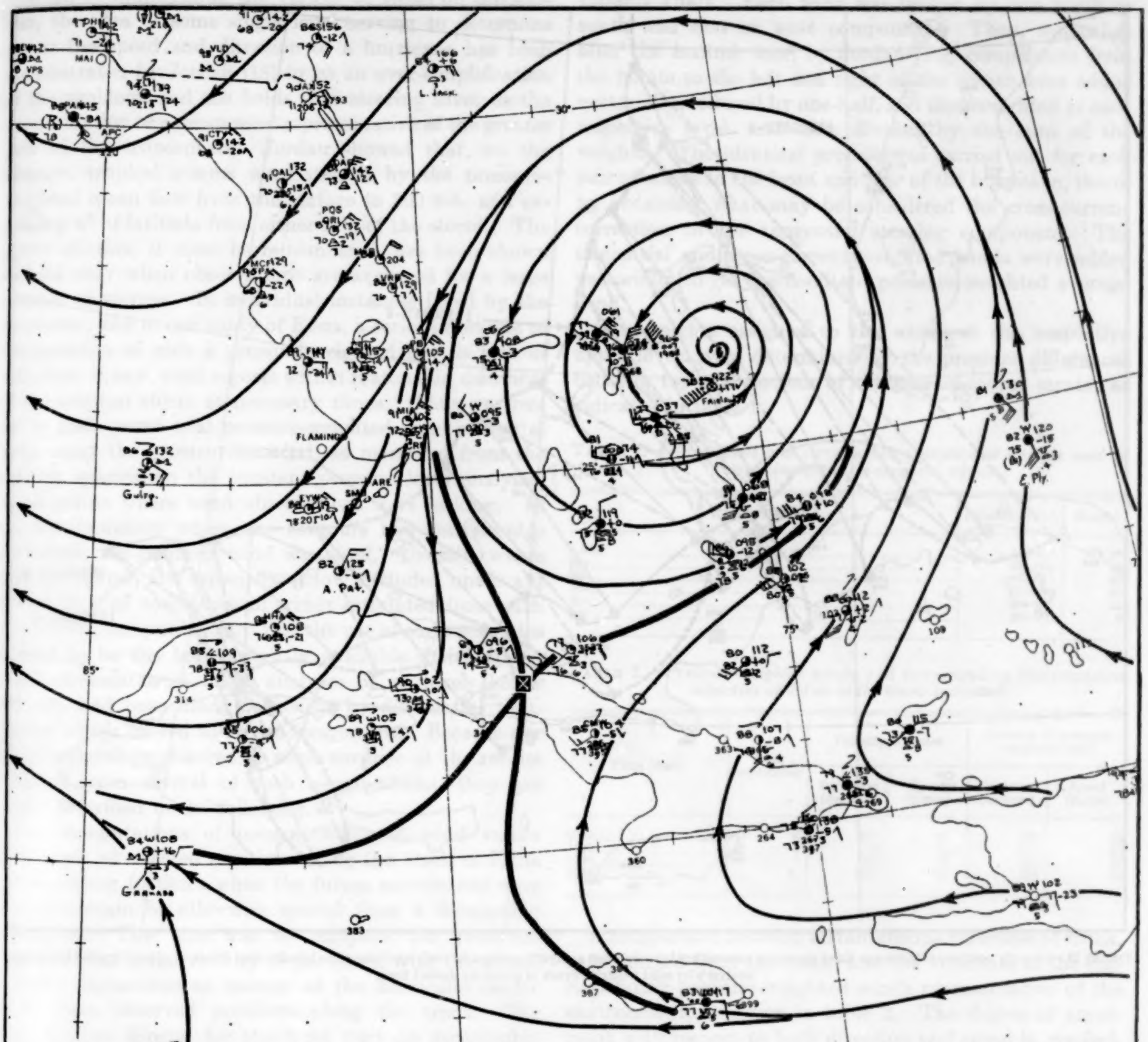

FIGURE 12.—Sample surface streamline analysis (as prepared under operational conditions). Heavy lines illustrate axes of inflow and outflow, and "X" marks the hyperbolic point. Data are from surface weather reports for 1830 GMT, September 8, 1954.

analysis of Edna for the surface level. As our interest was in the value of such an analysis from an operational standpoint under time limitations our streamlines were sketched rapidly, based on only hasty judgments concerning the reliability of questionable wind reports. The period selected for the analysis was from 0030 GMT September 6 to 0030 GMT September 10 inclusive, an interval which covered all the 6-hourly surface maps from the time of formation of Edna until just after recurvature would have been evident from the usual indications.

Following the procedure of Sherman and Carino [12], the analyses were performed by two analysts working independently. In figure 13 we have superimposed the track of the hyperbolic points obtained by one analyst over that obtained by the other, as a means of comparing the extent of agreement between them. This summary of the tracks of the hyperbolic points may be compared with a similar figure given by Sherman and Carino [12]. We have no intent of drawing any general conclusions from just this one case, of the usefulness in current synoptic practice

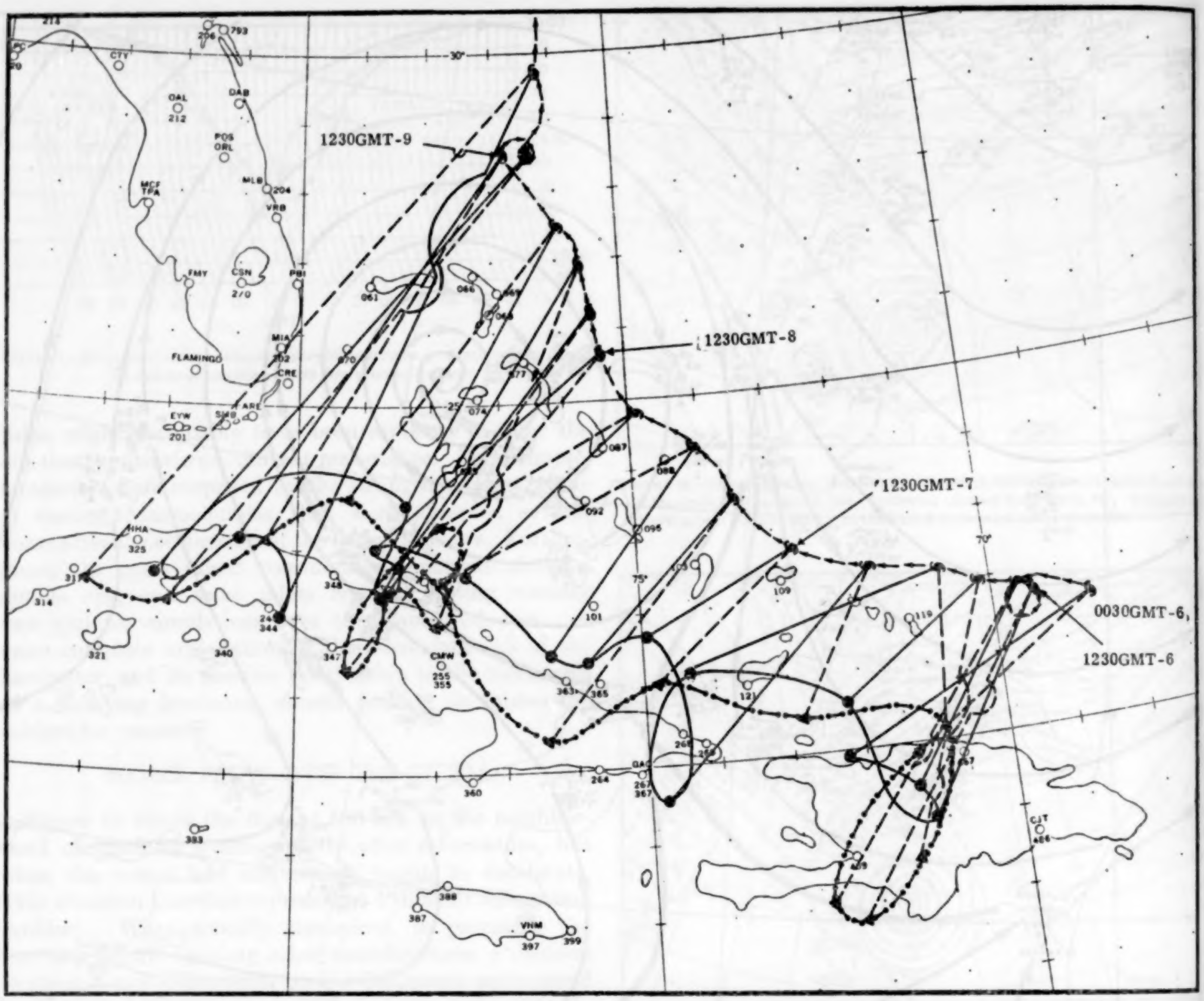

FIGURE 13.—6-hourly positions of hurricane Edna shown by conventional symbol; first analyst's position for the hyperbolic point by solid dots (track of points by solid line), second analyst's by solid triangles (track of points by dashed line).

of analyzing with special attention to the hyperbolic point. We were impressed in several instances by the inability of the analysts to reach reasonably close agreement on the location of the point, due principally, we all felt, to sparsity of data. From an after-casting standpoint, there are indications that at those times when the storm center is moving more erratically and slowly, such as when looping, the hyperbolic point fluctuates correspondingly.

STEERING ASPECTS

In attempting to forecast the movement of hurricanes, meteorologists have for many years given considerable attention and a wide range of interpretation to the rather vague concept of steering. Some interpretations of the steering principle are based on reasoning as stated by James [15] that "if a vortex is embedded in a constant wind field it will move in the direction of the general wind, and the maximum wind around it will have the same direction owing to the mutual reinforcement of the two systems." "This," James continues, "is the kinematic basis of the forecasting rule that a closed pressure system tends to move in the direction of the strongest wind about it." Because it is necessary "to identify a general circulation of dimensions large compared with those of the individual vortices, prognostications of the kinematic theory are valuable only in the case of disturbances of small dimensions such as tropical cyclones." Like many other forecasting precepts, there have been instances when steering has appeared to give erroneous results or has been difficult to apply because of data deficiencies, as for example in the case of typhoon Doris, 1950 in which different steering results were obtained by different analysts (see [16] and [17]).

Without enumerating the variety of views on the subject, the idea of some single level serving to determine *per se* the speed and direction of a hurricane has been demonstrated by Jordan [18] to be an over-simplification of the problem, and she holds that steering involves the determination of a mean wind representative of the greater part of the troposphere. Jordan showed that, on the average, tropical storms were steered by the pressure-weighted mean flow from the surface to 300 mb. and extending 4° of latitude from either side of the storm. The above relation, it must be remembered, has been shown to hold only when observations are averaged for a large number of storms. In individual instances faced by the forecaster, and in our study of Edna, a serious obstacle to computation of such a pressure-weighted flow is lack of sufficient, if any, wind reports within reasonable distances of the tropical storm at necessary times. Thus we were led to make some trial pressure-weighted wind computations using the geostrophic wind, as measured from the contour spacing on the constant pressure level analyses, at all points where wind observations were lacking. In the few instances where the contours had considerable curvature, the gradient wind was used. Usually, where data are sparse, and especially at low altitudes, one is apt to feel lack of confidence in winds estimated from such geostrophic computations. But the use of such estimates seemed to be the best currently available under operational circumstances. The analyses of all levels below 200 mb. had been made consistent by differential techniques, which offered some encouragement. Because our initial misgivings changed to some surprise at the results obtained from several of such computations, they are briefly described in the following.

The computations of pressure-weighted wind values were made at selected positions along the track of Edna corresponding to times when the future movements were most uncertain or otherwise crucial from a forecasting standpoint. The aim was to compare the pressure-weighted wind in the vicinity of the storm with the actual observed instantaneous motion of the hurricane center taken from observed positions along the track. The computations depend for the most part on geostrophic approximations that would have been available to the forecasters.

Four points at 6° of latitude from each storm center location were taken for evaluation; one point to the left and another to the right, and one to the front and another to the rear of the storm. The distance of 6° of latitude was selected because such a radius, with respect to the average size of Edna along this portion of the track, extended to just beyond the area of winds moving in an apparently closed circulation. The hurricane was assumed to be vertical at all times. The winds were determined over each point at 1,000, 850, 700, 500, 300, and 200 mb. Thus, winds from each of the constant pressure analyses regularly prepared in the WBAN Analysis Center were weighted, with the exception of those from the 150-mb. chart. Each wind was broken up into north or south and east or west components. Then, somewhat after the manner used by Jordan [18], components from the points to the left and right of the center were added vectorially, reduced by one-half, and then weighted at each respective level, and then divided by the sum of the weights. The identical process was carried out for each pair of winds to the front and rear of the hurricane, thereby obtaining what may be considered the cross-current correction to the tangential steering component. The tangential and cross-current weighted winds were added vectorially to get the resultant pressure-weighted average wind.

The weights assigned to the winds at the respective upper levels were determined by the pressure differences between top and bottom of the corresponding strata, as indicated in table 1.

TABLE 1.—*Wind levels and corresponding strata and weights used in computing pressure-weighted winds*

Wind level (mb.)	Stratum (mb.)	Weight
1,000	1,000-900	100
850	900-800	100
700	800-600	200
500	600-400	200
300	400-250	150
200	250-200	50

TABLE 2.—*Pressure-weighted winds and corresponding instantaneous velocities of Edna at the times indicated*

Time (GMT)	Date September	Velocity of center		Velocity of pressure-weighted wind	
		Direction (degrees)	Speed (knots)	Direction (degrees)	Speed (knots)
0300	6	115	10	100	08
1500	6	115	7.5	110	07
1500	9	205	5	200	07
0300	11	210	24	220	28

A comparison between instantaneous velocities of Edna, as estimated from the track, and the velocities of the corresponding pressure-weighted winds representative of the environment, is shown in table 2. The degree of agreement with respect to both direction and speed is, we feel, encouraging for further individual applications of the pressure-weighted wind technique. The results also seem to reflect credit on the consistency obtained from the differential techniques used in the preparation of the constant pressure analyses. It was noted that in the first two computations when the storm was moving essentially westward, the actual velocity of the center was slightly to the north of the direction given by the pressure-weighted wind. An interesting speculation is that this might be accounted for by what has been called the Rossby effect, by which cyclonic vortices in the Northern Hemisphere are subjected to a slight poleward acceleration due to the variation of the Coriolis parameter across the width of the storm [19].

A semi-objective technique for the prediction of tropical

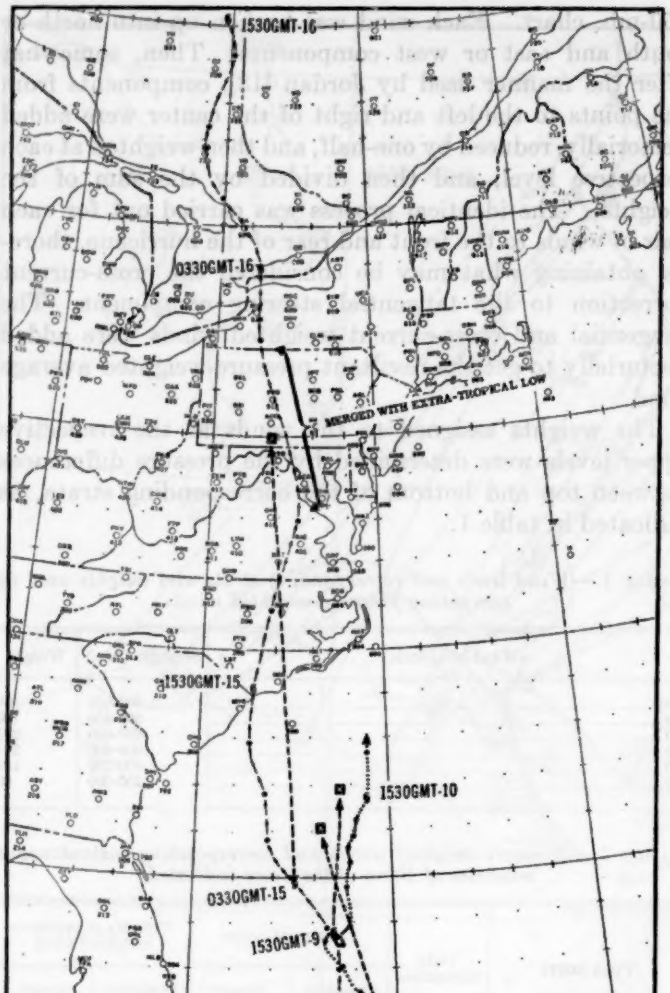

FIGURE 14.—Portions of the observed tracks of Hazel and Edna. The dashed lines ending at the "X's" denote the computed positions 24 hours from the time shown at the beginning of the dashed lines.

cyclone tracks, patterned after the methods used by George and collaborators [20], for forecasting the 24-hour displacement of extratropical storms, has been tentatively established by Riehl and Haggard [21]. While recognizing the influence of the overall tropospheric current, operational exigencies led Riehl and Haggard to search for parameters that would be approximately equivalent to the mean tropospheric flow, yet be based solely on the contour heights at 500 mb.

The Riehl-Haggard computation involves the recording and subsequent manipulation of a set of 500-mb. height values read at points determined by a somewhat variable grid over and surrounding the hurricane center. As the development of the method admittedly emulated the techniques employed by George [20], one is not surprised to find a graph and "types" entering into the calculations. This new technique, incidentally, like the method we used to compute pressure-weighted winds, is indirectly but strongly dependent on geostrophic approximations, and therefore presupposes painstakingly prepared analyses. Furthermore, in making either the pressure-weighted wind or Riehl-Haggard computations, groups of several independent readings or steps are involved, making it difficult to introduce any bias into the final result.

The Riehl-Haggard method was applied once along the track of Edna, when at upper air sounding time the center happened to be located in a critical position with respect to the forecast, and also applied three times along the track of hurricane Hazel, 1954, when the center was similarly located. Because these few trials of this new technique gave useful forecasts in situations selected for their complexity and difficulty, the results have been listed and depicted in table 3 and figure 14, respectively. At those times when the storm center is moving quite slowly, as at 0300 GMT October 10 in the case of Hazel, it is reasonable to expect the forecast system to give much better results for speed than for direction. As can be seen from figure 14, this was the case. Furthermore, the computation made at 0300 GMT on the 15th for Hazel which gave a result that was too slow, may not have been a fair trial of the method, which was not intended to predict movement "after the first day following final recurvature." Judging from these few applications further use of the technique is warranted.

TABLE 3.—*Results of Riehl-Haggard computations at several selected positions along tracks of hurricanes Edna and Hazel, 1954*

Hurricane	Date 1954	Time GMT	Location of center of storm at prog. time	24-hr. displacement of storm in degrees of latitude N–S, in degrees of longitude E–W	
				Actual	Predicted
Edna	9 Sept.	1500	28.6N, 76.5W	3° to N 1° to E	3.2° to N 0.2° to E
Hazel	10 Oct.	0300	14.6N, 75.5W	1° to N 0.2° to E	0.6° to N 0.9° to W
Hazel	14 Oct.	1500	26.4N, 75.4W	7.7° to N 3.4° to W	4.9° to N 1.6° to W
Hazel	15 Oct.	0300	30.0N, 77.7W	14° to N 1.2° to W	10.1° to N 0.6° to W

Charts of mean temperature (thickness) for the 700 to 500-mb. stratum at times shortly after recurvature, 0300 and 1500 GMT, September 10, have been prepared by Simpson [4], and the track that Edna followed does provide an additional case in support of Simpson's theory [22] of warm tongue leading and steering of tropical cyclones.

ACKNOWLEDGMENTS

John J. Smiles of the WBAN Analysis Center gave the authors invaluable assistance by preparing several of the figures, and checking many of the computations.

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Charts of mean temperature (isotherms) for the 700-to 500-mb. layer at times shortly after recurvature, 0300 and 1500 GMT, September 10, have been prepared by [illegible] (figs. 11b and 12b). [illegible] follow [illegible] pattern as [illegible] in support of Simpson's [illegible] upper warm [illegible] during the [illegible] of tropical cyclones.

ACKNOWLEDGMENTS

John J. [illegible] of the WBAN Analysis Center gave the authors invaluable assistance by preparing several of the figures and checking some of the computations.

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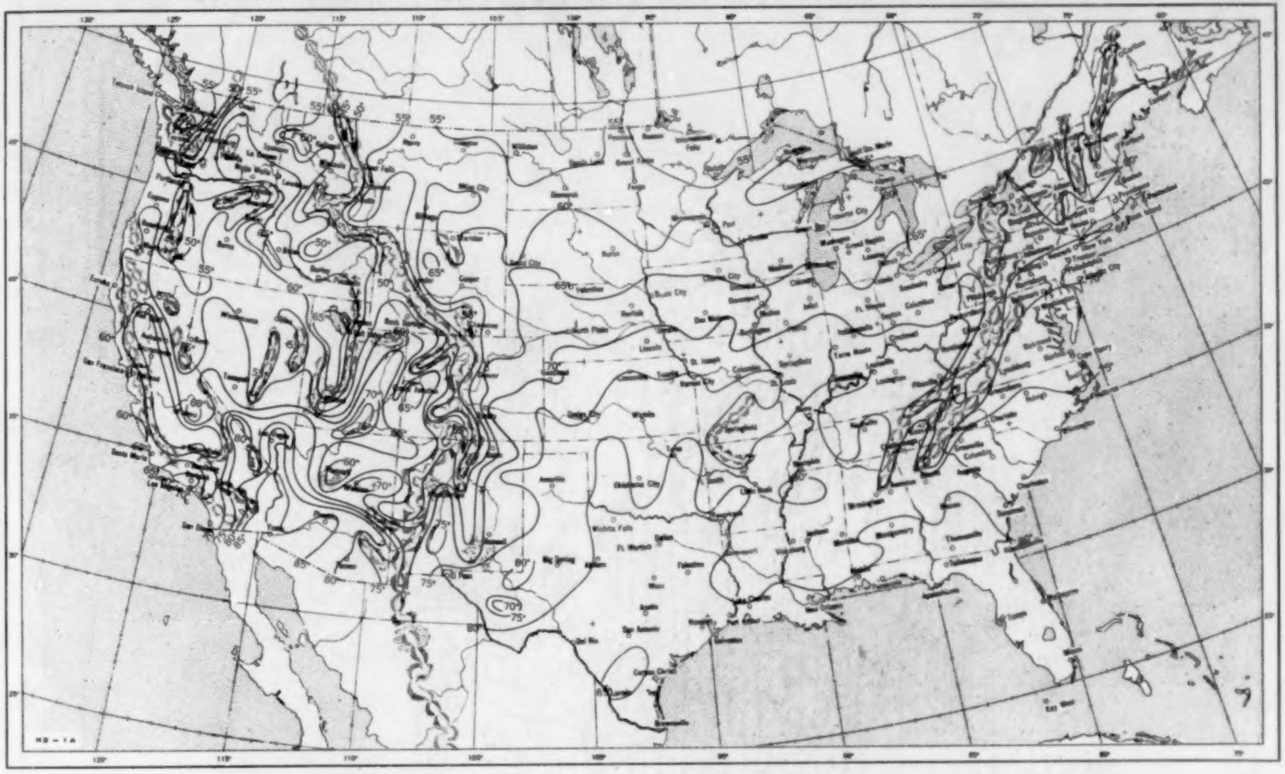
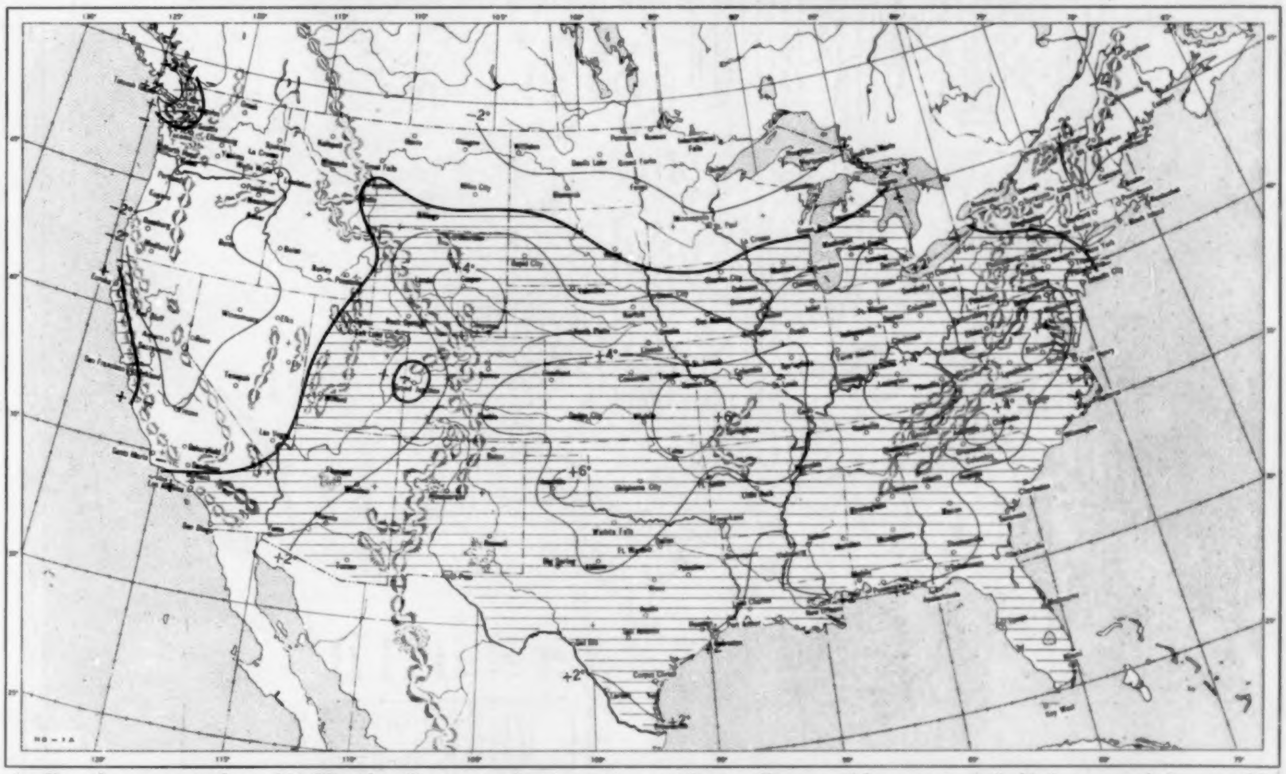
Chart I. A. Average Temperature (°F.) at Surface, September 1954.

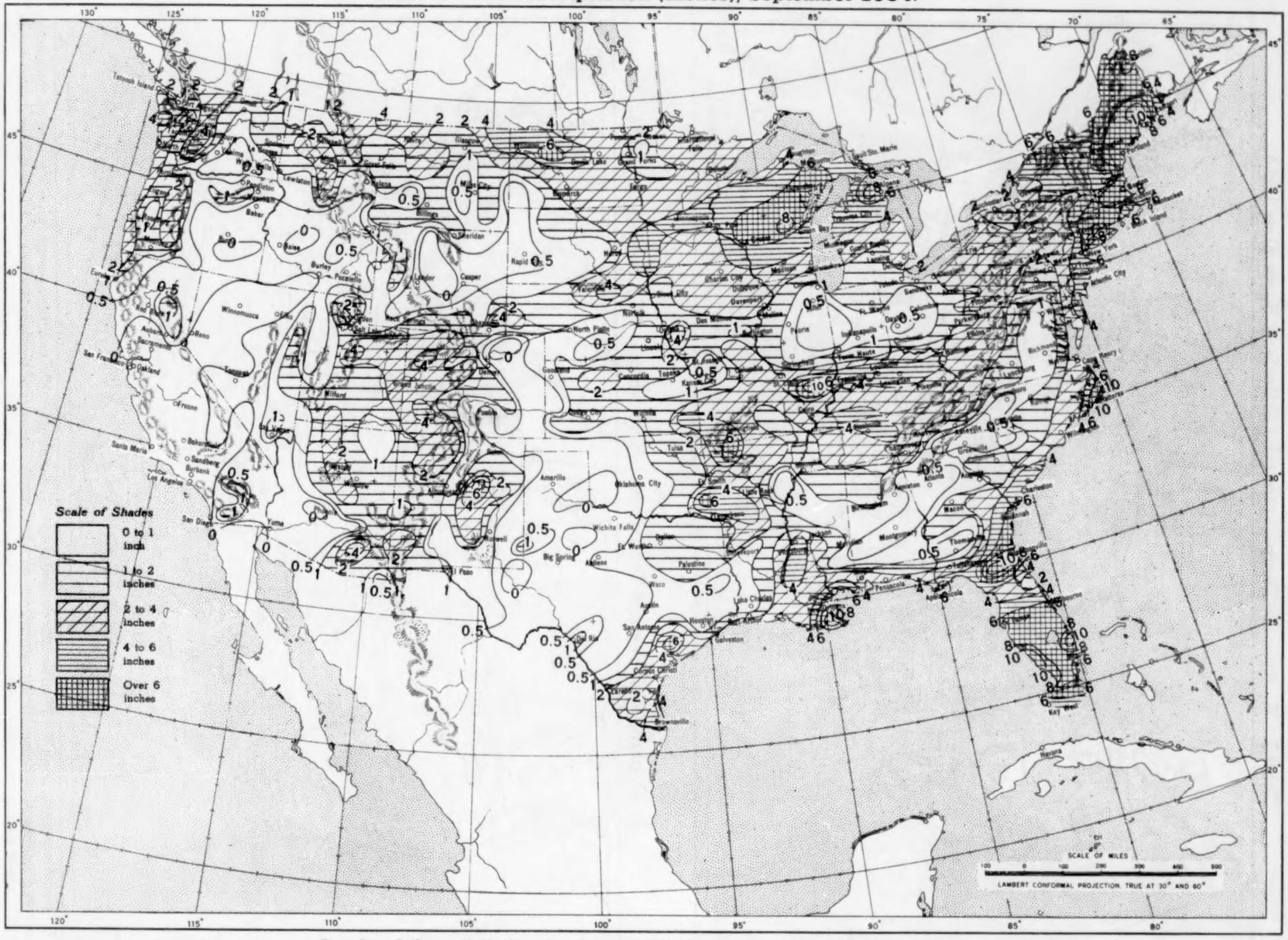


B. Departure of Average Temperature from Normal (°F.), September 1954.



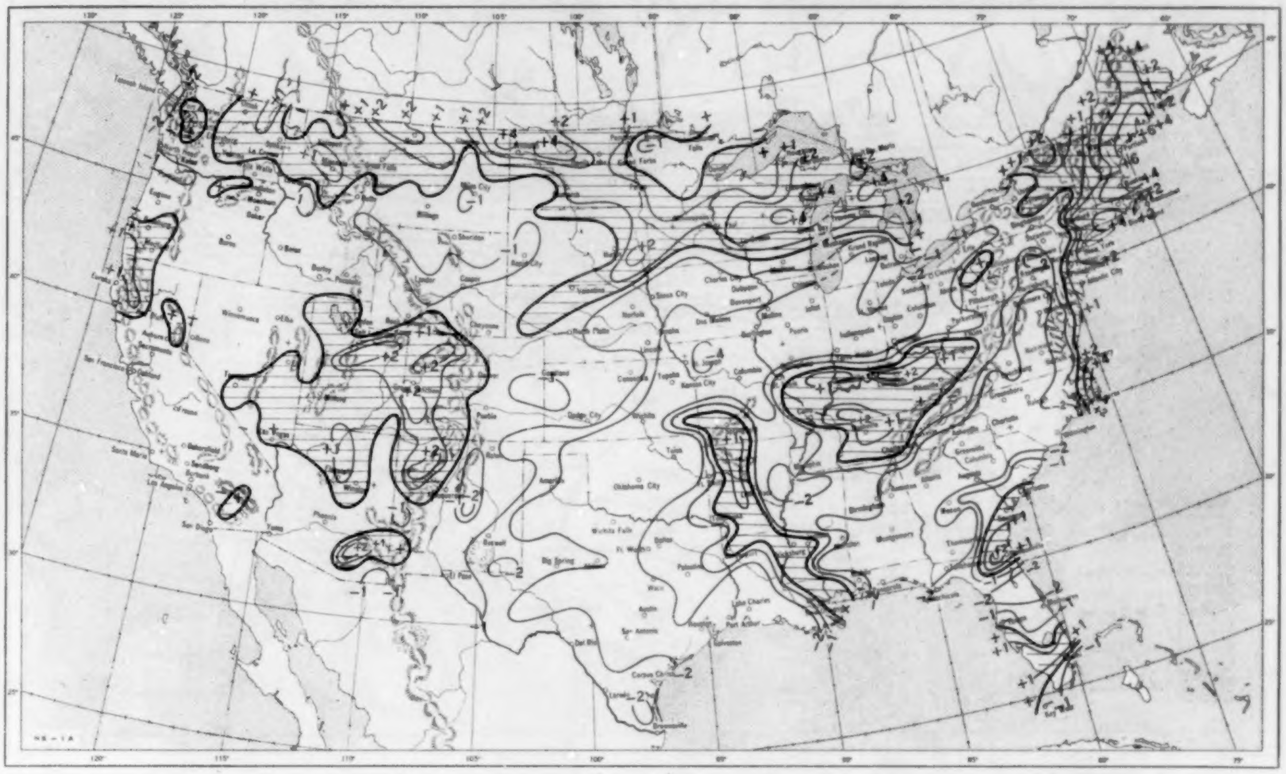
A. Based on reports from 800 Weather Bureau and coöperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), September 1954.

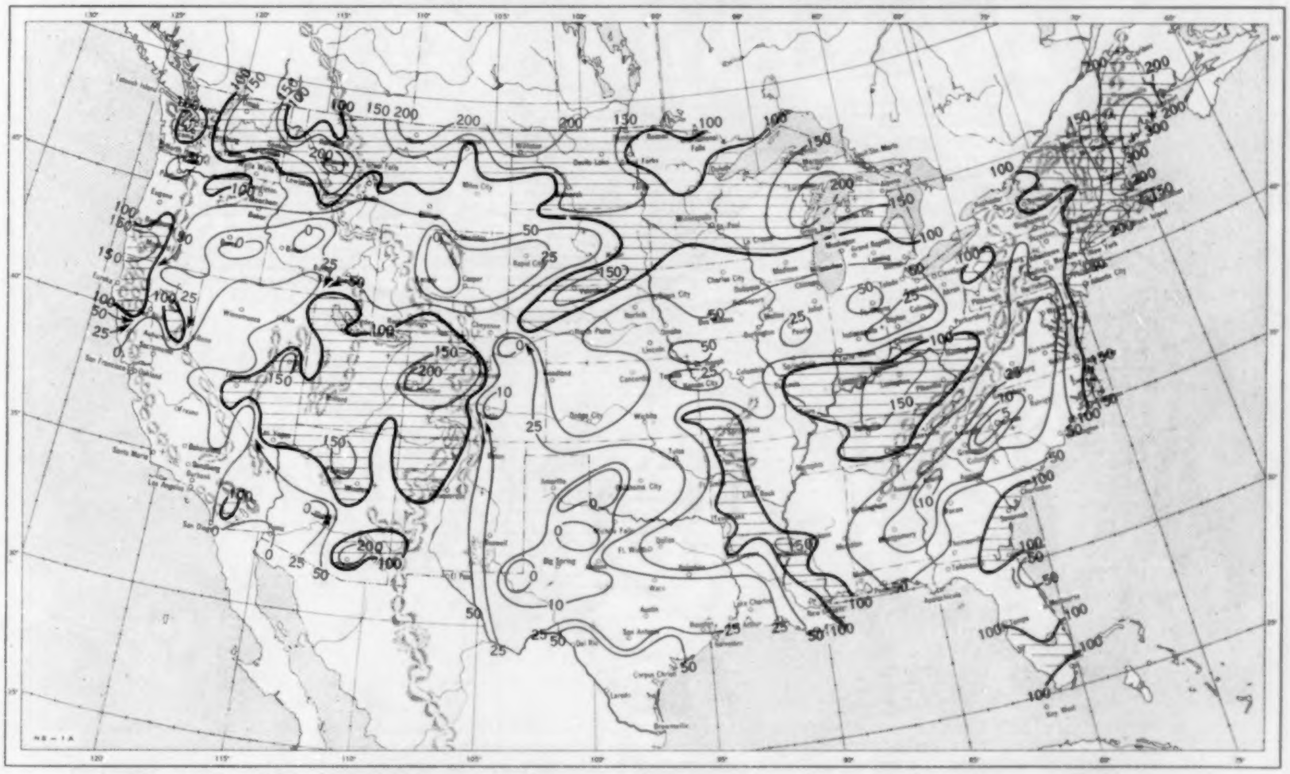


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), September 1954.

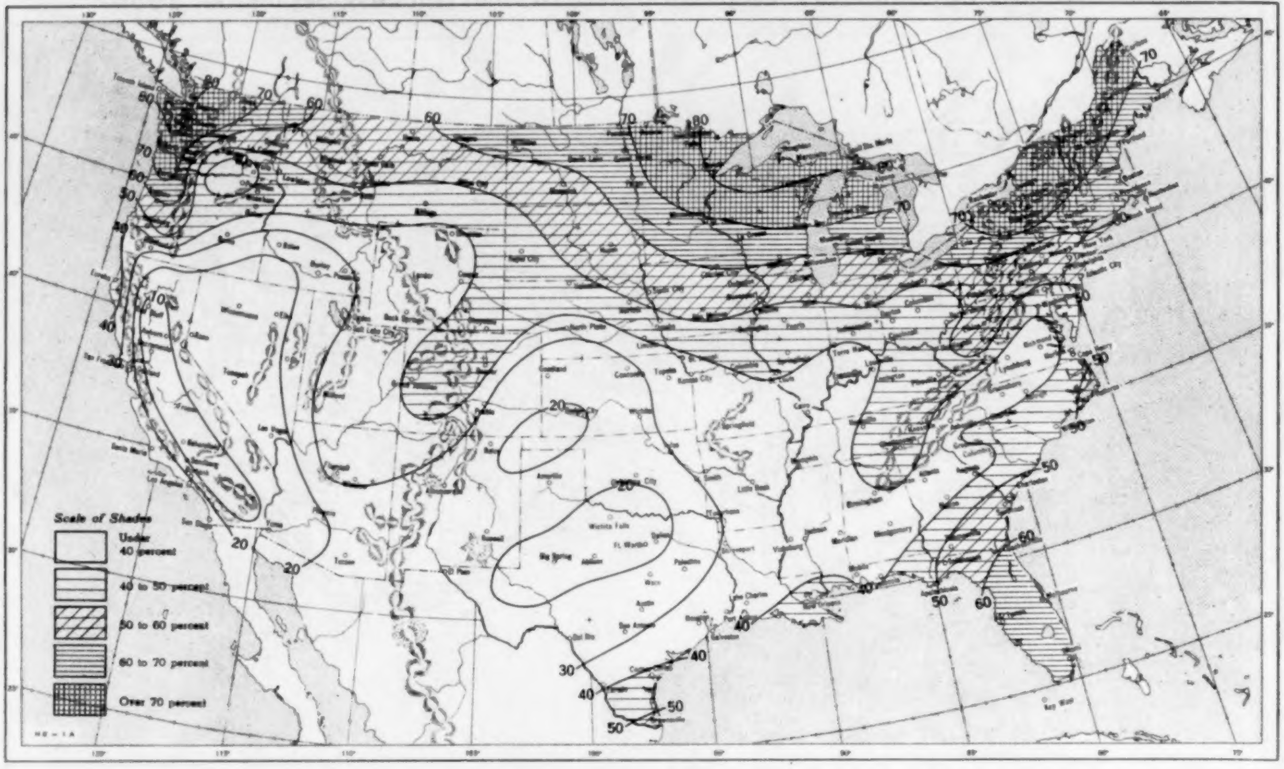


B. Percentage of Normal Precipitation, September 1954.

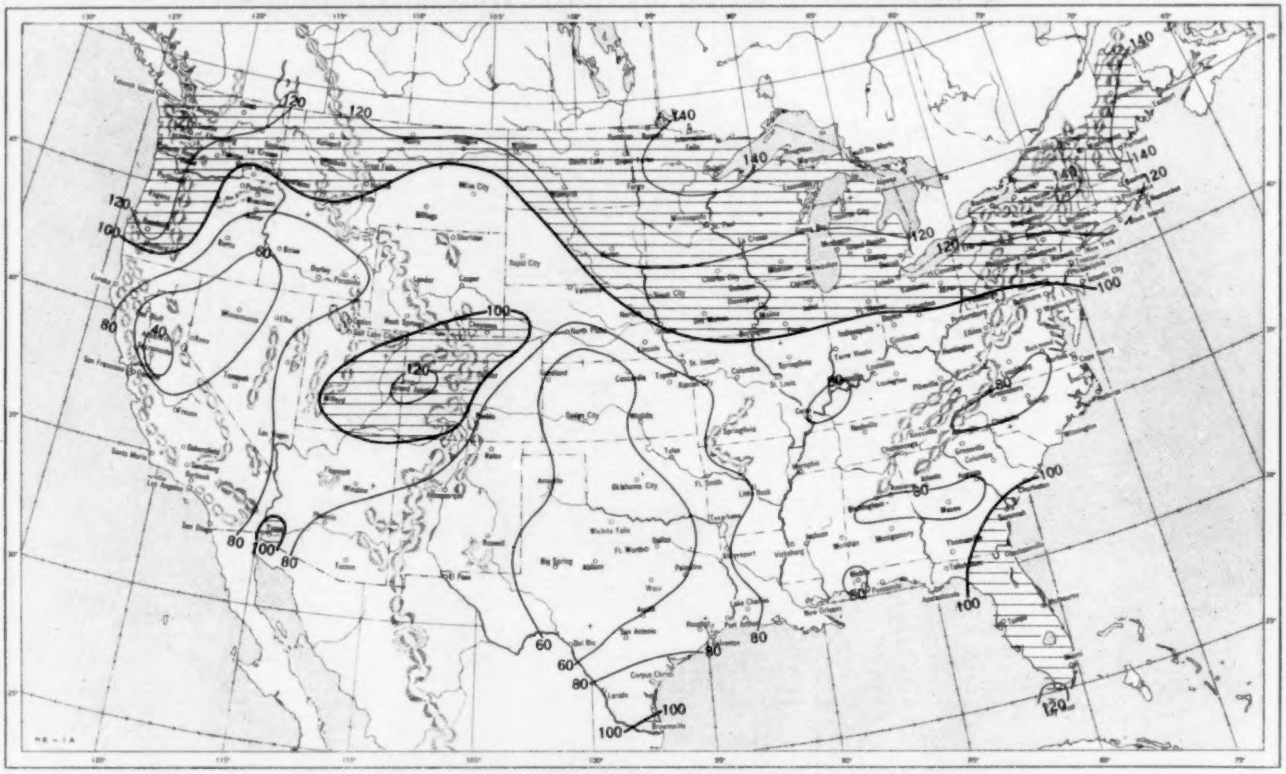


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, September 1954.

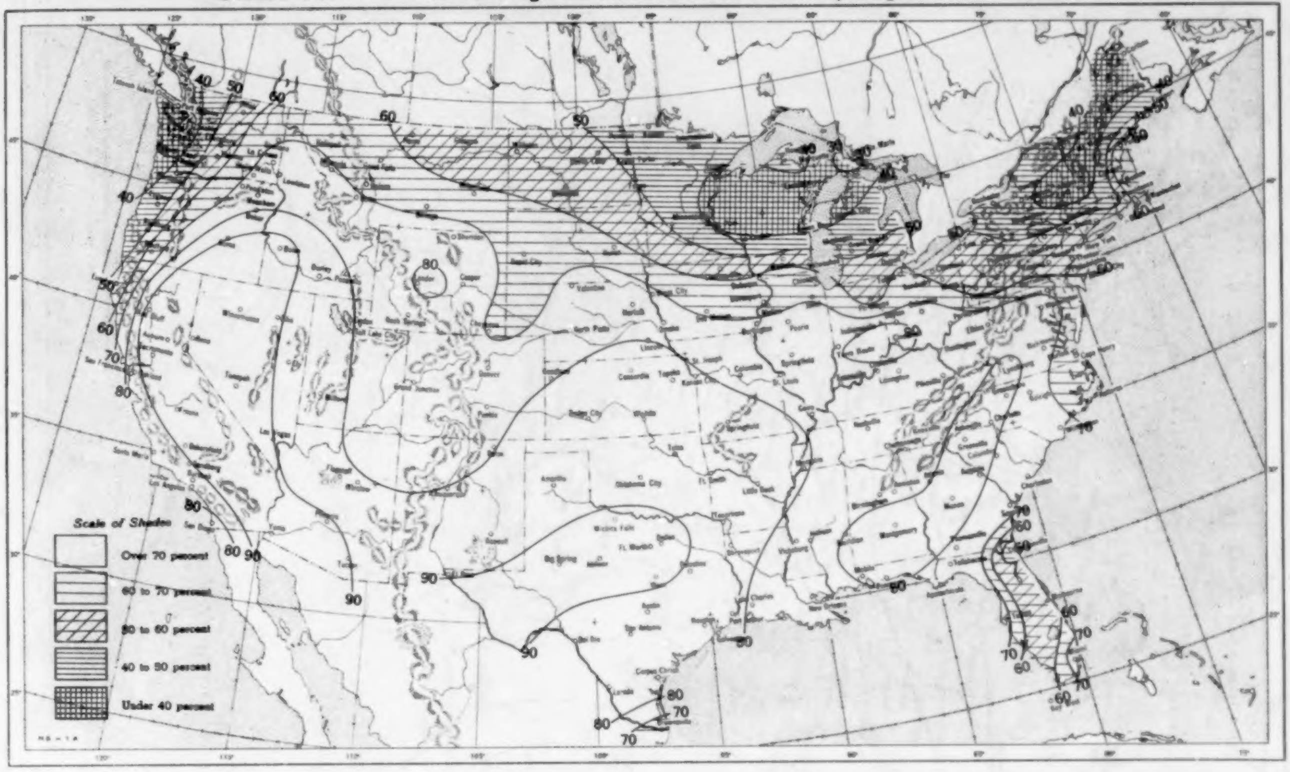


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, September 1954.

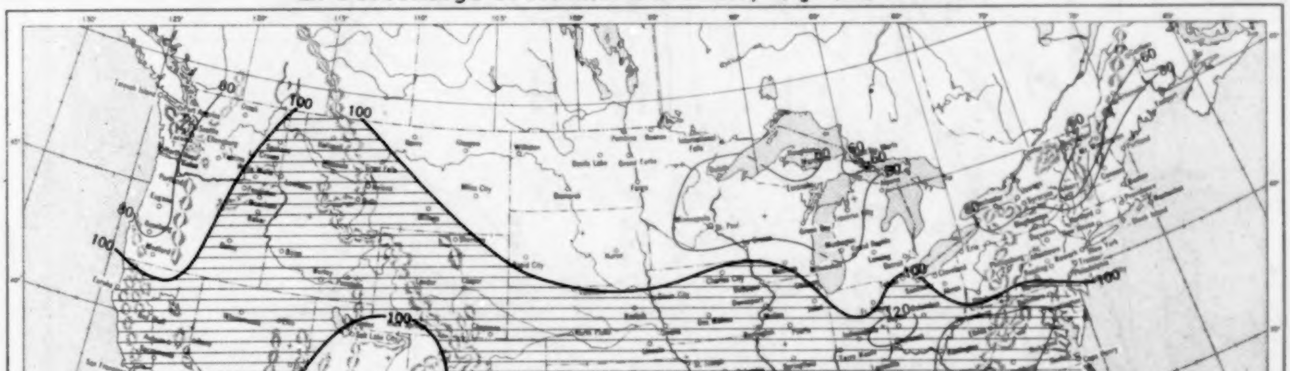


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, September 1954.



B. Percentage of Normal Sunshine, September 1954.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, September 1954. Inset: Percentage of Normal Average Daily Solar Radiation, September 1954.

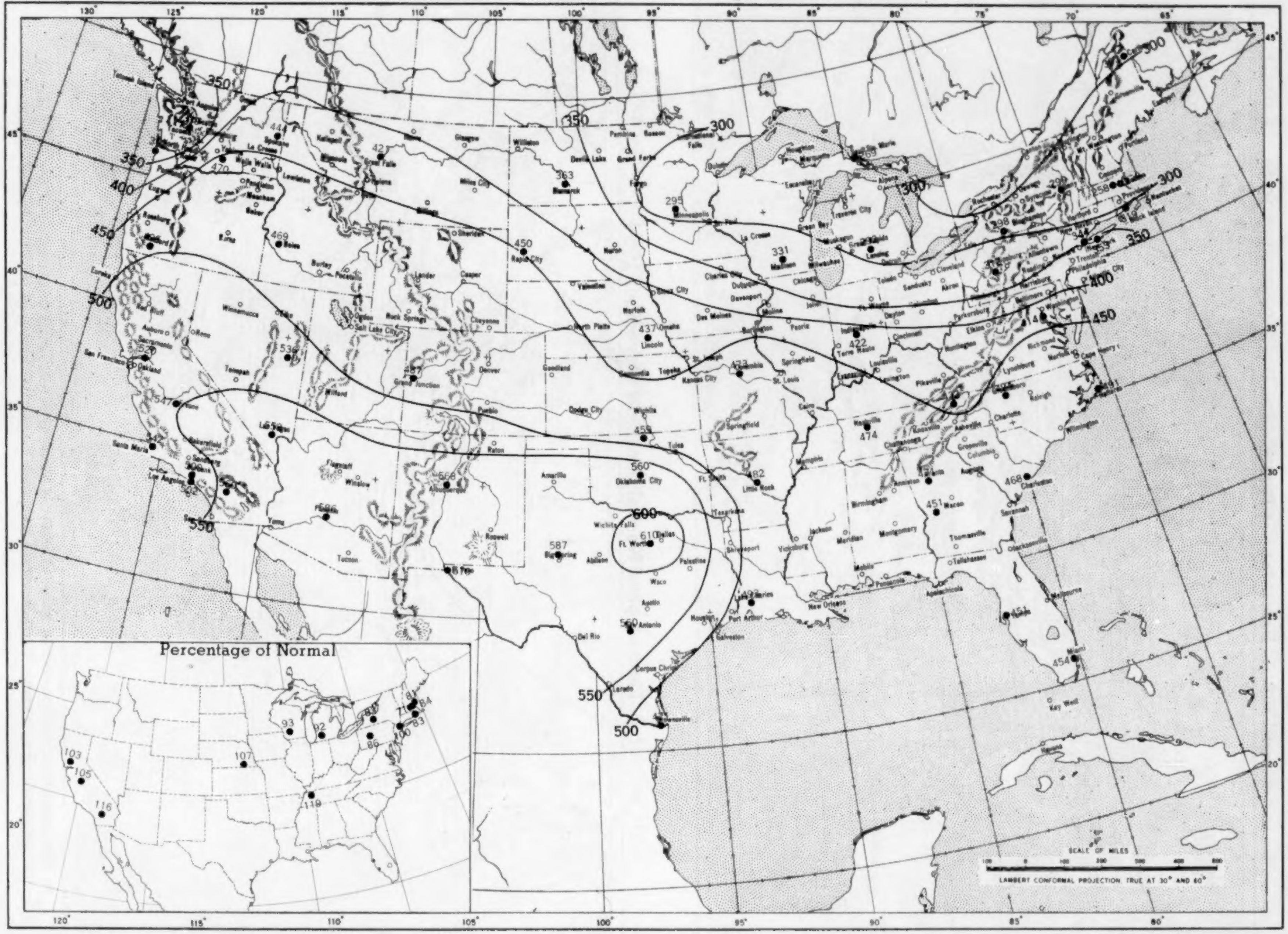
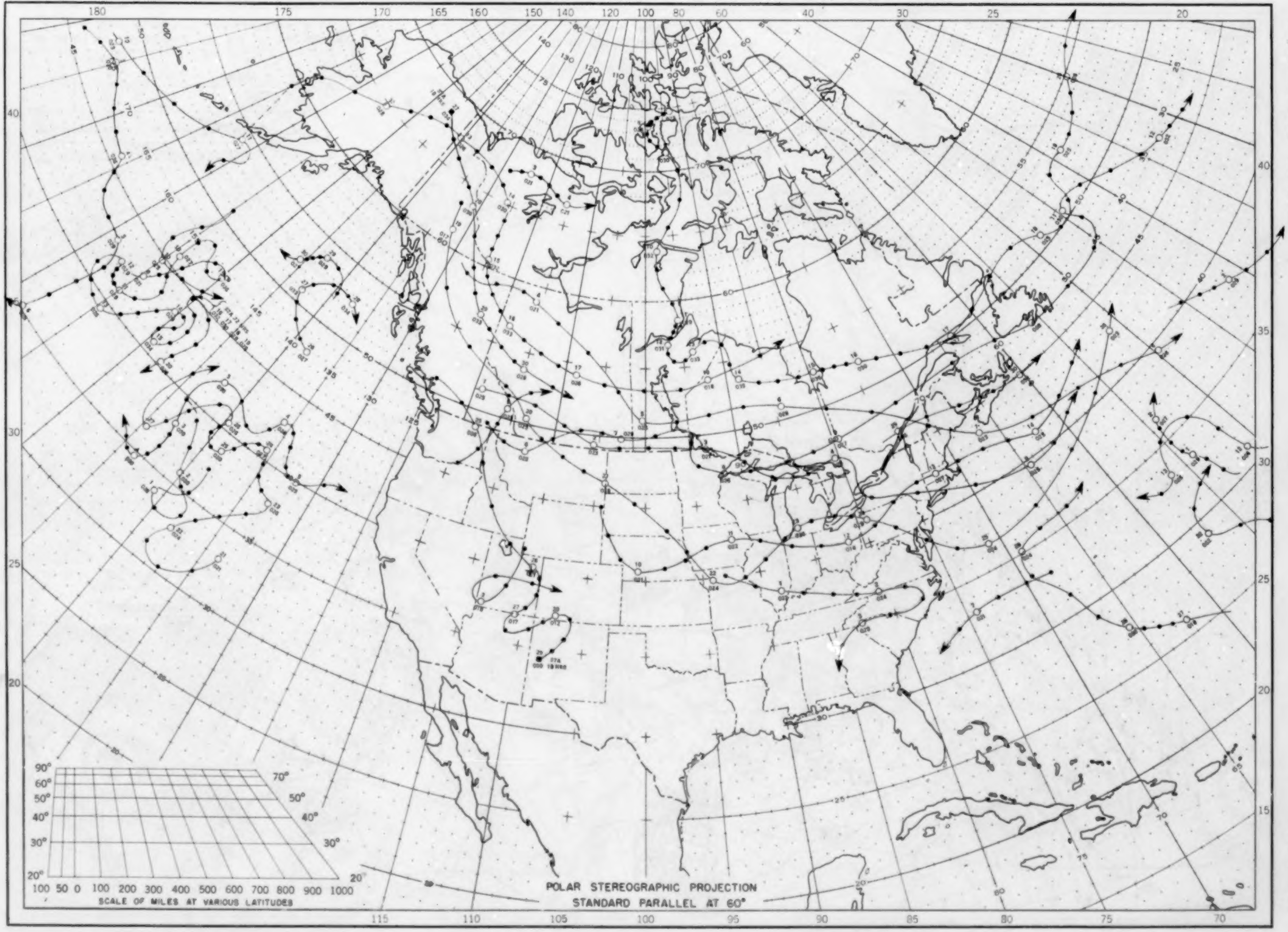


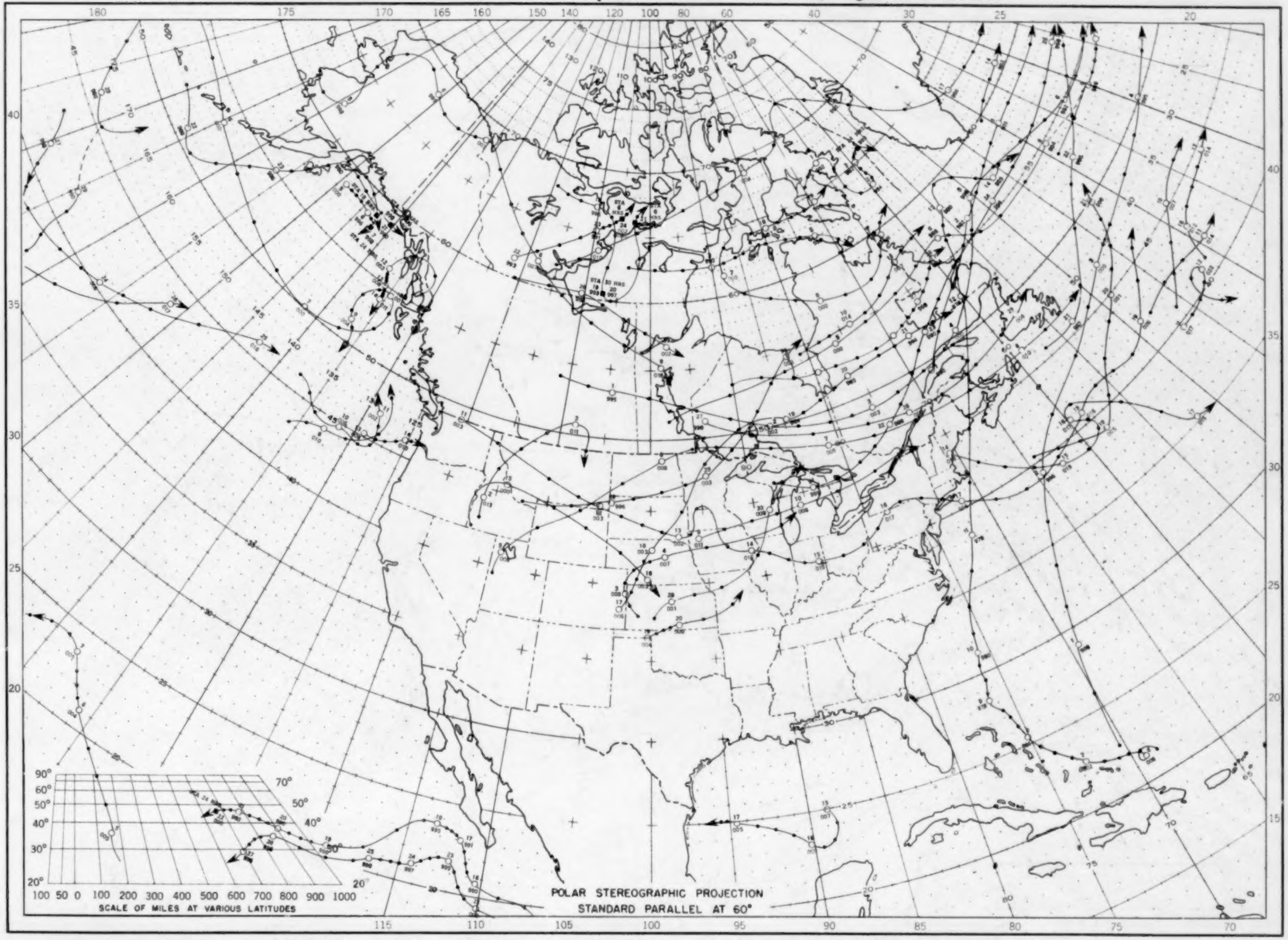
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.⁻²). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, September 1954.



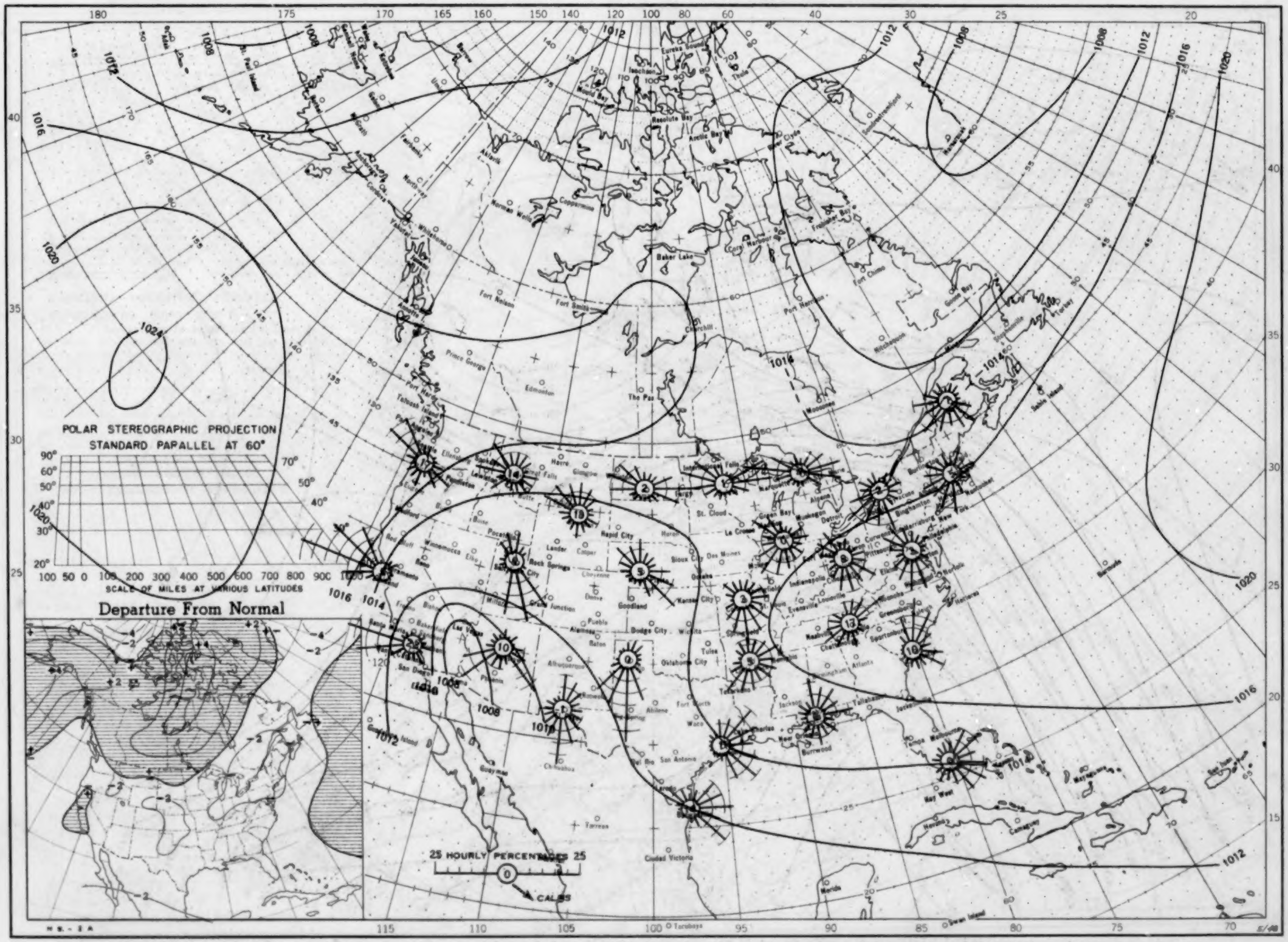
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, September 1954.



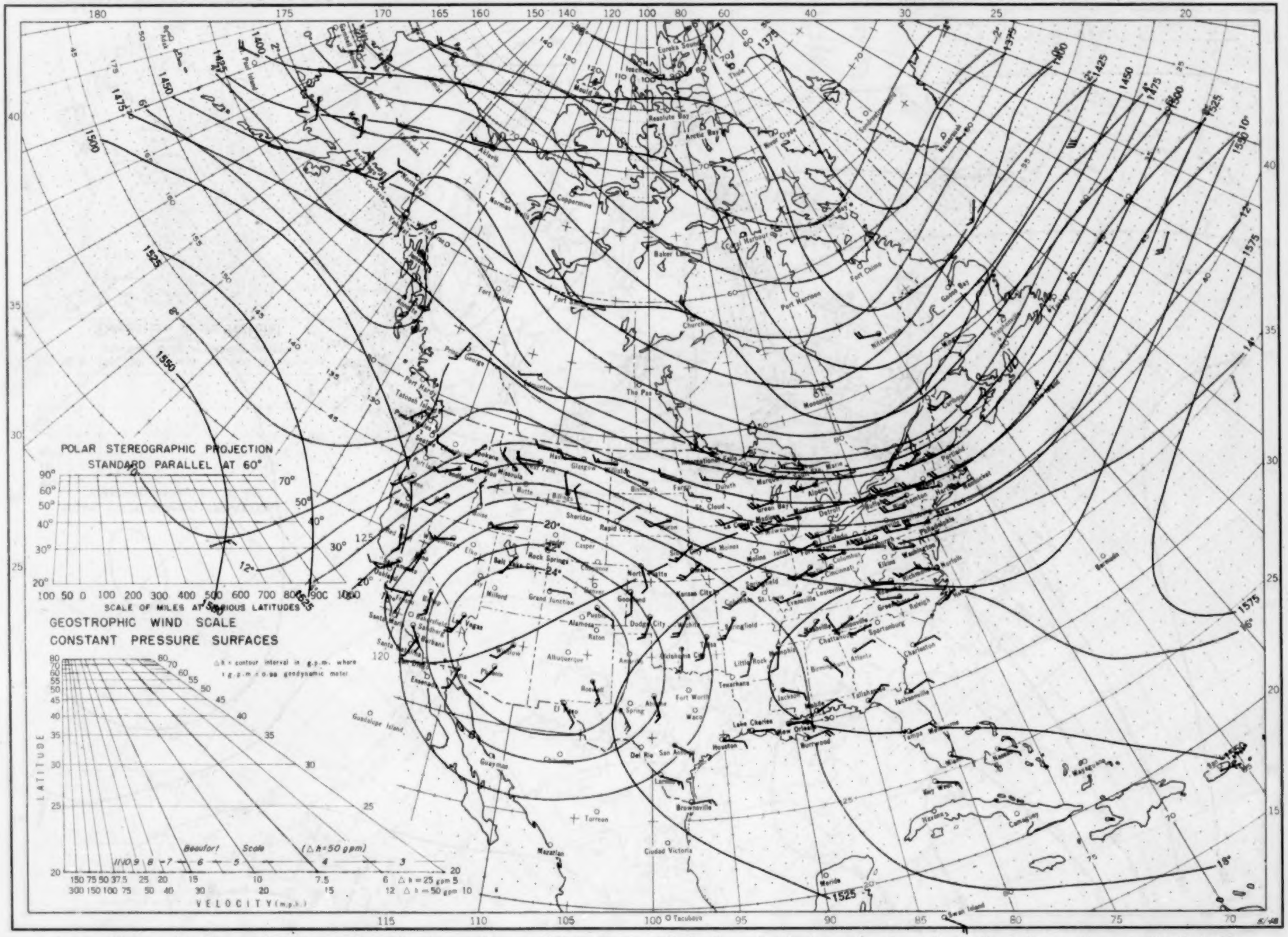
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, September 1954. Inset: Departure of Average Pressure (mb.) from Normal, September 1954.



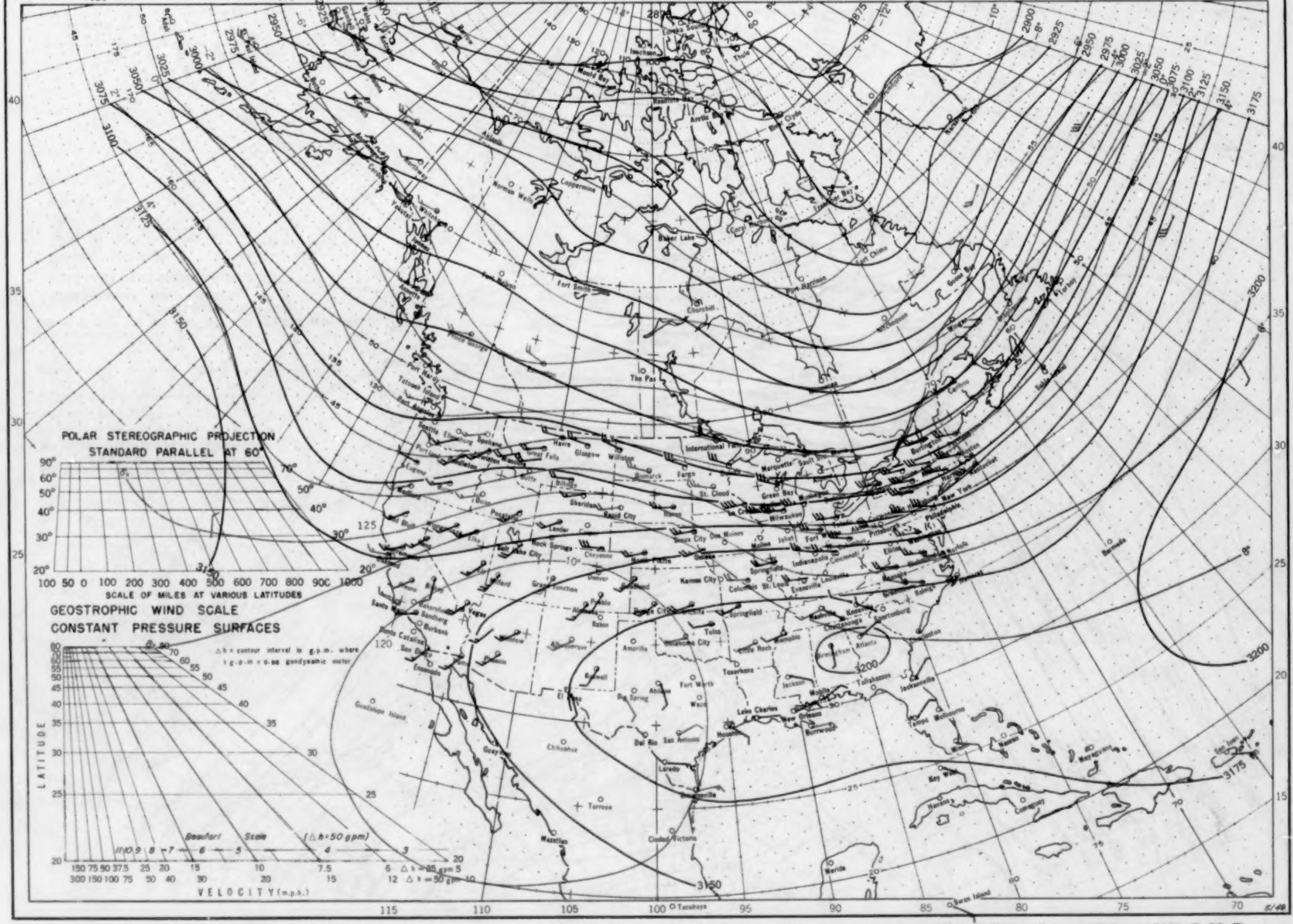
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), September 1954.



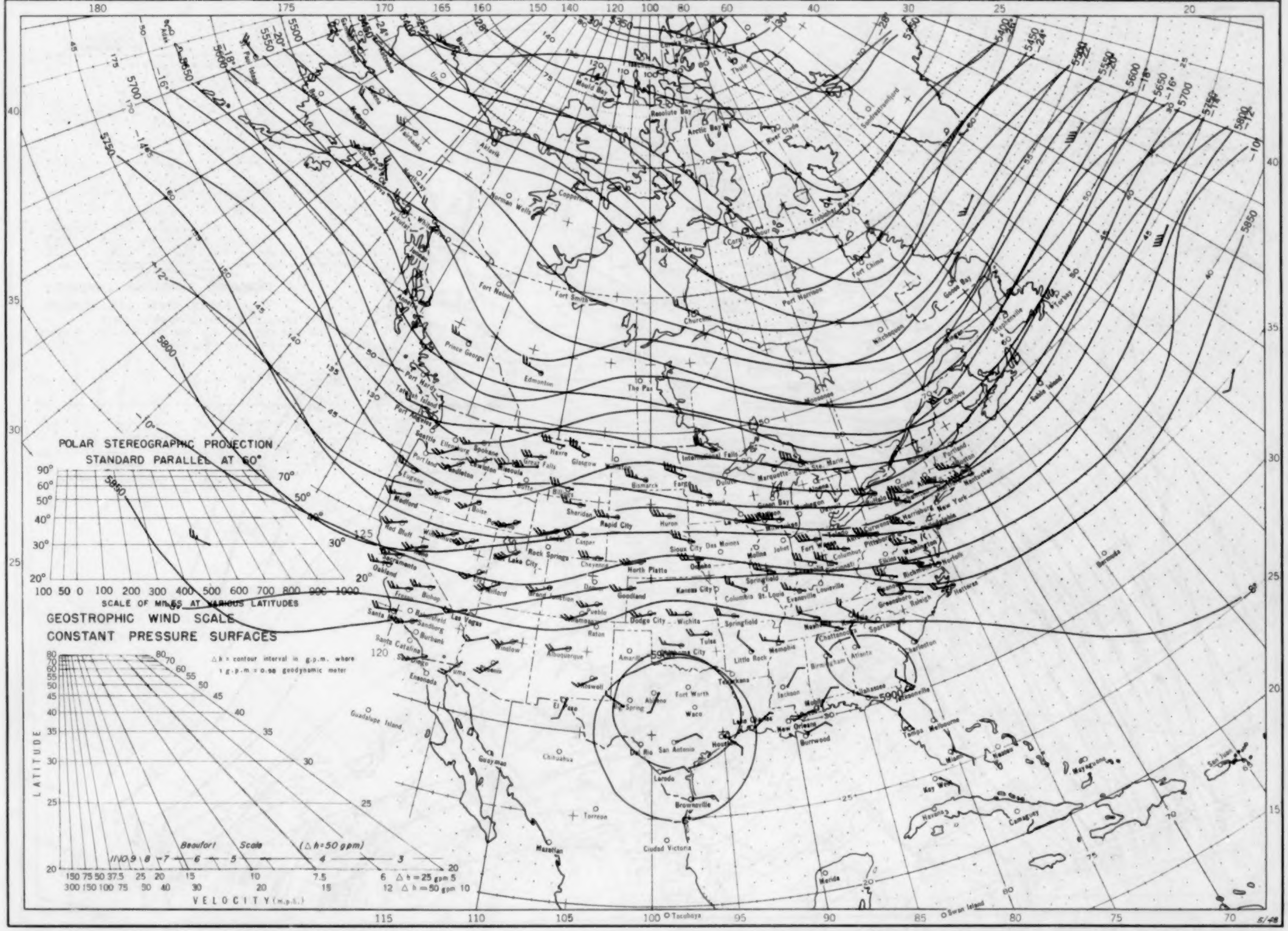
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), September 1954.



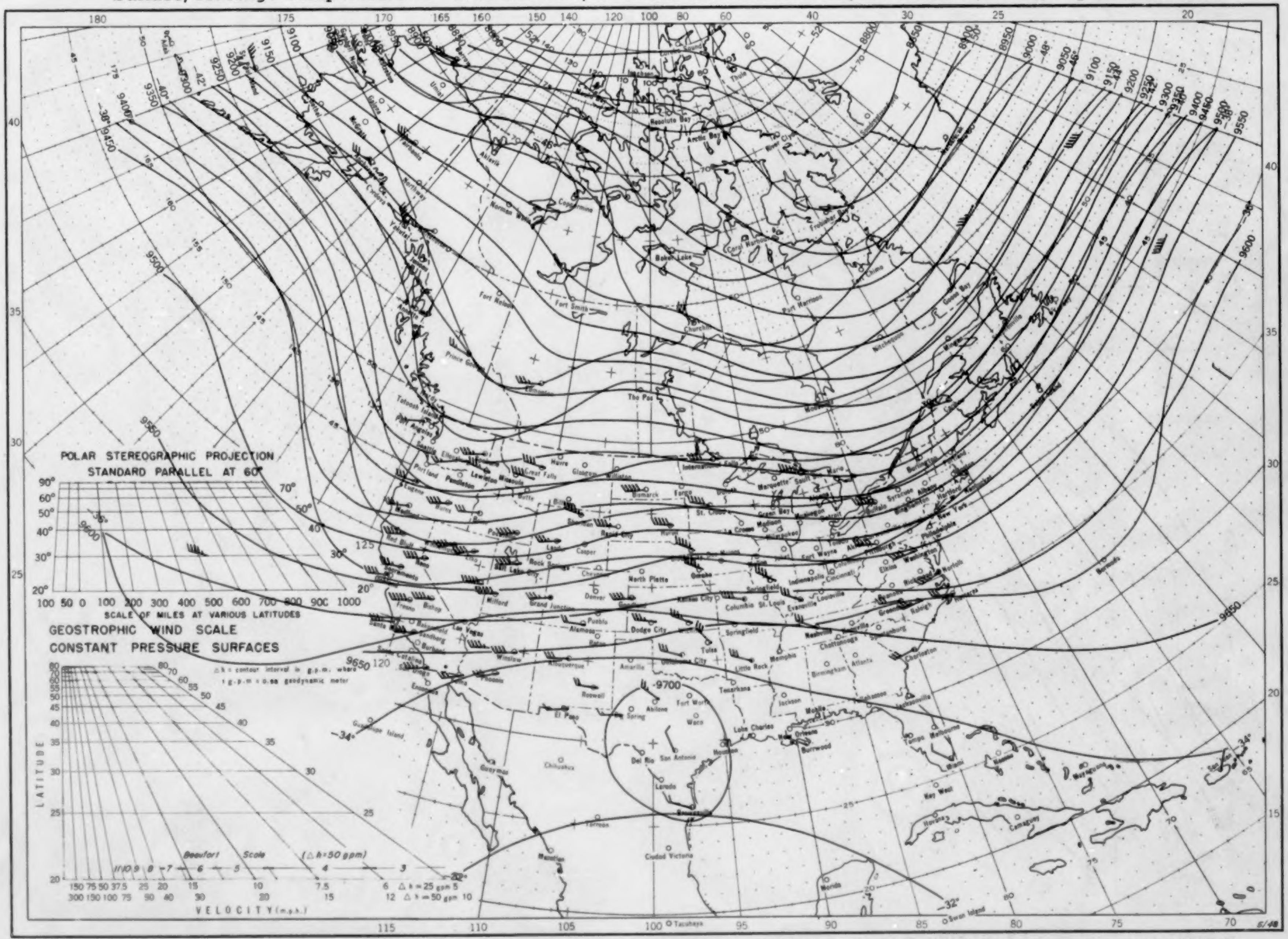
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), September 1954.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), September 1954.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.